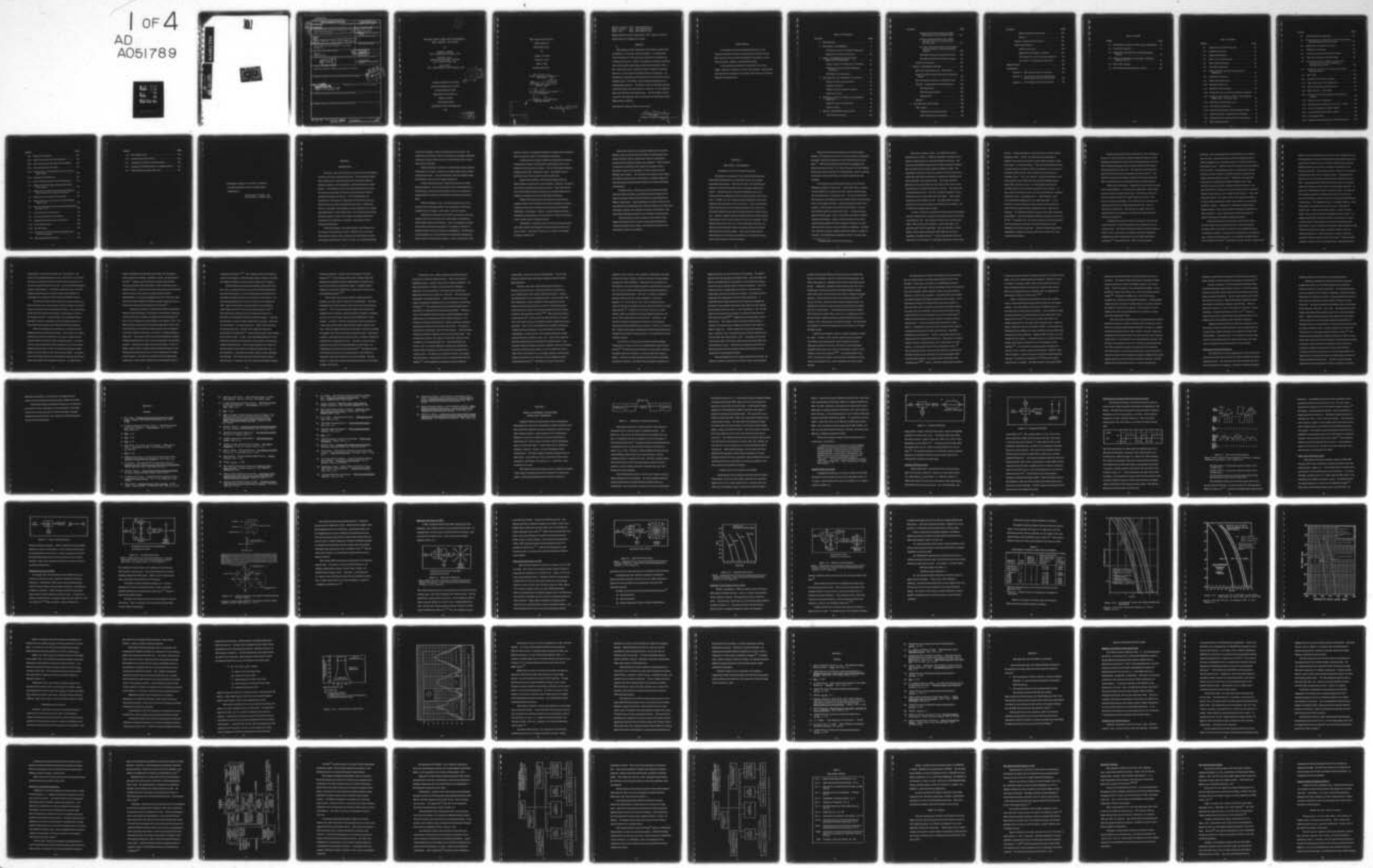
AD-A051 789 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO F/G 17/2.1
MILITARY DIGITAL MICROWAVE TRANSMISSION: PAST, PRESENT, FUTURE.(U)
AUG 77 R E BRACKETT, W E CARTER, J J SOLTIS
UNCLASSIFIED AFIT-CI-78-45 NL

1 OF 4
AD
A051789



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER AFIT-CI-78-45	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Military Digital Microwave Transmission: Past, Present, Future		5. TYPE OF REPORT & PERIOD COVERED 9 Master's Thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Ronnie E. Brackett, Warren E. Carter [redacted] John J. Soltis		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT Students at the University of Colorado, Boulder CO		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/CI WPAFB OH 45433		12. REPORT DATE 11 Aug[redacted] 1977
		13. NUMBER OF PAGES 299 Pages
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 314p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release; Distribution Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES APPROVED FOR PUBLIC RELEASE AFR 190-17. JERRAL F. GUESS, Captain, USAF Director of Information, AFIT		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)		

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

012200

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(1)

MILITARY DIGITAL MICROWAVE TRANSMISSION: PAST, PRESENT, AND FUTURE

by

Ronnie E. Brackett
B.S., Montana State University, 1970

Warren E. Carter
Johns Hopkins University, 1952-1955
A.A., Cochise College, 1971

John J. Soltis
B.S., United States Air Force Academy, 1970

A project submitted to the Faculty

of the Telecommunications Program

in partial fulfillment of the

requirements for the degree of

Master of Science

Telecommunications

Department of Electrical Engineering

1977

This Project for the Degree of

Master of Science

Telecommunications

by

Ronnie E. Brackett

Warren E. Carter

John J. Soltis

has been approved by

S.W. Maley

Warren L. Flock

I. Jack Kerner

Robert J. Williams

Date 10 August 1977

Brackett, Ronnie E. (M.S., Telecommunications)
Carter, Warren E. (M.S., Telecommunications)
Soltis, John J. (M.S., Telecommunications

Military Digital Microwave Transmission: Past, Present, and Future

Project directed by Professor S.W. Maley

ABSTRACT

This project treats the transmission of information in digital form over Military, line of sight, microwave systems. A concise history of the development of PCM technology is presented as a foundation for a discussion of technical, political, and regulatory problems encountered when converting from a fully analog system and environment to first, a quasi-digital environment, and then to a future all digital environment. Interwoven, are the motives for digital microwave transmission, and the functional relationships and dependencies which occur between various regulatory bodies, the Military, and the industrial manufacturers of communications hardware. The Military's Test and Evaluation approach to the DCS system conversion problem is examined, as is the implementation of the Military's first digital system. The final chapter provides an overview and perspective of the actions taken and of the Military future digital systems capability.

This abstract is approved as to form and content.

S. W. Maley

S. W. Maley
Chairman, Advisory Committee

Acknowledgments

As co-authors of this telecommunications project we wish to express our thanks and sincere appreciation to our project advisors and to all those in the government and industrial communities who provided information, guidance, and outstanding support.

A very special type of thanks is lovingly given to our wives, Gladys, Margaret, and Marion, for their encouragement, understanding, and continuing love during this year of study at the University of Colorado, Engineering Graduate School.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE		PAGE
6-1	PCM/TDM System Configuration	106
6-2	RF Spectrum for 12.6 Mbps Three-Level Partial Response (VICOM) Digital FM-3 MHz Deviation	108
6-3	Digital Radio Link Margin Assessment	111
6-4	PCM/TDM Flow Diagram	114
6-5	Performance Assessment Functional Diagram	116
6-6	TDM Signal Degradation Meter Indication	119
6-7	RF Spectrum Using a 6.9 MHz Notch Filter and a 6.9 MHz Carrier for Various Multiplex to Orderwire Ratios (MOR)	123
6-8	Typical Test Configuration for Three-Level Partial Response Format	127
6-9	BER vs RSL	130
6-10	Proposed DTAP Test Site Locations	133
6-11	Typical BER vs RSL Test Configuration	141
6-12	Bit Error Rate Summary (Theoretical)	142
6-13	BER vs RSL (R = 19.804 Mbps)	143
6-14	Bit Error Rate vs Receive Signal Level (Saturation Region)	144
6-15	Typical C/I Test Configuration	146
6-16	Swept Frequency Interference Curves (C/I = 15 dB) . .	147
6-17	Co-channel Interference (FDM on QPSK).	148
6-18	Co-channel Interference (FDM on QPR)	149
6-19	C/I at Higher RSL's	150
6-20	Emitted Spectrum Amplitude and Baseband Deviation . .	152

FIGURE		PAGE

FIGURE		PAGE

"ALTHOUGH CONGRESS CAN MAKE A GENERAL, IT TAKES COMMUNICATIONS TO MAKE HIM A COMMANDER."

General Omar N. Bradley, USA
From his book, A Soldier's Story

CHAPTER 1

INTRODUCTION

The world, in the last two decades, has experienced a technological revolution in electronic component technology. This has opened countless doors of opportunity in telecommunications for development engineers, production engineers, and subsequently, the telecommunications system designer. The transistor and other solid state technology has provided an economical and practical contribution to the development of digital modulation techniques and their use. The rising demands for the transmission of information in a digital form by commercial enterprise and the Military has made it apparent that in the future, a fundamental resource, knowledge, and the ability to acquire and update it on a regular and continuing basis, will be highly valued. The communications manager and system engineer must be able to integrate emerging information of recognized user requirements, technology, and economics into the existing knowledge bases.

As the world changes, the resulting impact on the Military must be assessed, for the Military is surely a reflection of the civil world. The solution to complex military requirements is often found in commercial industry and institutions of higher learning. One can hardly deny that

a great deal of thought, energy and enterprise goes into science, and especially into that part of science which guides an increasingly complicated technology in doing new things and also in doing old things more economically and more efficiently.

Modern technology is forcing the communications systems engineers and managers to recognize, interpret and analyze changes within the field of telecommunications. One such technology is that of the digital modulation techniques which are used in digital transmission.

To fully understand the role of digital-transmission in military telecommunications, one must start with the history and fundamentals of the technologies concerned and the problems which were encountered in implementing the technologies into the Defense Communications System (DCS).

With these thoughts in mind, this project discusses one area in the broad field of telecommunications--the transmission of information in digital form over military, line of sight, microwave systems.

The purpose of this project is to provide an awareness of the many problems which may be encountered in implementing a communication system which employs new technologies. This is accomplished in regard to the military communication problem by (1) building a solid base of applicable digital microwave transmission methodologies, (2) developing an understanding of the relationships between industrial development and Military usage of communications hardware, and (3) relating some of the

technical, political, and regulatory problems associated with the implementation of a system to satisfy a communications requirement.

A concise history of digital modulation and transmission techniques is developed in Chapter Two along with the motivations for their use in military terrestrial microwave systems. The use of the digital techniques in high frequency (HF), tropospheric scatter, and satellite links are beyond the scope of this project and will not be addressed.

Chapter Three identifies, discusses and compares different digital modulation techniques as to their utilization, efficiency, and impact on an already congested radio frequency spectrum. Some of the current uses of these digital modulation techniques are presented along with new modulation techniques which are currently under development.

Chapter Four focuses briefly on the national and international regulatory bodies which formulate policy and provide guidance necessary to keep both commercial and military telecommunications compatible. Additionally, the regulatory, political, and quasi-technical problems encountered in implementing a military system are related with emphasis on the resultant impact on military hardware.

Consequently, an industrial survey of commercial equipment that was readily available and adaptable for Military usage was made in the early seventies. The results of this survey, as well as a 1977 update are given in Chapter Five.

Based on the results of the commercial equipment survey and the Military's desire to increase their knowledge of available digital transmission techniques and their application to microwave transmission, several test and evaluation programs were established. These programs are discussed in Chapter Six with respect to the purpose of each, a description of what was accomplished, and how it acted to meet the Military's requirements. Also reflected in this chapter are the cooperative advances made by industry, government, and military agencies in achieving mutual progress toward the finalization of viable technologies and equipments.

In Chapter Seven, a description of several commercial digital microwave links and systems is provided along with an insight into the types of equipments employed and the rationale for their application to Military requirements. System performance parameters which evolved from testing and evaluating these pilot links and systems are also discussed. The chapter concludes with a detailed examination of the Military's pilot quasi-digital transmission system that was installed in central Europe.

The final chapter provides an analysis of the Military's quasi-digital transmission system to include radio propagation predictions, frequency congestion and its impact, and concludes by focusing on the future digital systems of the Military.

CHAPTER 2

WHY DIGITAL TRANSMISSION?

An Historical Overview of Digital Transmission

The historical development of Voice Channel Digital Coding and Time Division Multiplexing is the cornerstone for the current digital transmission technologies. Since the mid-1930's, the communications industry has witnessed remarkable success in multiple-channel transmission. During this period, this fact was attributed to the use of Frequency Division Multiplexing (FDM) of signals along the transmission wires. In FDM, the entire frequency range is divided into narrow-band segments with one assigned to each voice channel. There were problems of noise and interference between adjacent channels which could only be overcome through the use of costly and complex filters for channel separation. Nonlinear amplifier and cable amplitude and phase versus frequency characteristics cause a serious problem referred to as crosstalk. Crosstalk had various forms such as near-end and interaction crosstalk, but all forms had the destructive effects of attenuation of the desired signal and interference from other signals. Often, this crosstalk was the determining factor in the length and reliability of a transmission system, and it is still a problem to be dealt with today.

There were several partial solutions previously proposed by industry. One solution was to twist the wire pairs using the transposition principle to eliminate the undesired currents induced between the wire pairs.[1*] Other partial solutions included frequency staggering and physical separation of cables. H.S. Black's invention of inverse feedback greatly improved the linearity of the analog amplifier, thereby improving the system's overall performance, but it did not deal directly with crosstalk.

It was during this period that initial studies in Time Division Multiplexing (TDM) were being made. In this TDM scheme, channels are time-divided into a number of time slots with each channel having its own predetermined, repeated time slot. It was soon realized that this latter form of multiplexing was more ideally suited to the transmission of the various digital data forms. But the development of digital transmission, or the transmission of discrete separate pulses, was slow, and virtually retarded at certain points in time. An important point, which will surface again, is that, along with the development of digital transmission techniques, advances were also apparent in the analog systems thereby delaying the shift in emphasis to digital as was illustrated by Black's invention of inverse feedback in amplifiers. A definite, clear advantage in going to a digital transmission system was absent at this point, but its development progressed, however, at a slow pace.

---

[*] Footnotes appear at the end of each chapter.

Since voice is analog in nature, and comprised the bulk of information to be carried, a method for efficiently converting the voice signal to a digital format was required for digital transmission. This requirement prompted the experiments with pulse modulation techniques. The early efforts were in Pulse Amplitude Modulation (PAM). The continuously varying voice signal was sampled at certain discrete times, and the pulse generated was assigned an amplitude corresponding to the speech amplitude at the sampling instant. The series of pulses so generated was then transmitted over the medium to the receiver where the pulses were recovered and the process reversed. This scheme had certain drawbacks in that it, like FM, was highly susceptible to noise and distortion which greatly affected the pulse shape. PAM is highly dependent on good amplitude linearity. The pulses had to be shaped accurately to overcome the problem of crosstalk between channels, and to retrieve the original signal accurately.

In 1935, Alec Reeves of Standard Telecommunication Laboratories devised a modulation plan to help the communication system overcome the susceptibility to noise. This proposal by Reeves was to vary the pulse width, rather than the pulse amplitude, with the input signal. The generated pulses were of equal height. This was referred to as Pulse Width, or Pulse Duration Modulation (PWM, PDM) and was not as dependent on amplitude linearity.[2] This development fell short of its desired goal in the fact that it was still highly susceptible to the presence

of noise. A similar development occurred in the form of Pulse Position Modulation (PPM). In PPM, the amplitude of the analog signal is assigned a value which corresponds to a pulse shifted in position, either left or right, of a reference position. This also met with limited success. A partial solution to the effects of noise on the pulses was to increase the bandwidth in PDM and PPM, and to effectively increase the signal's immunity to noise. There was, however, a limit to the advantage which could be gained by this method due to the increased bandwidth requirements within a limited spectrum. It was during these tests that the cumulative effect of noise in multi-hop systems became apparent. In long, multi-hop transmission links, the noise encountered was cumulative through the system, compounding errors. Once introduced, these errors contributed significantly to voice signal degradation. It was felt that a far greater advantage could be gained to help overcome this effect if the voice signals could be multiplexed in time, rather than in frequency. The realization of this idea came two years after the development of PDM. Pulse Code Modulation (PCM) was invented by Alec Reeves in 1937.[3] During that year, the concept of PCM was not well-understood by the communications community, and the PCM process was not adaptable to the existing analog plant. The lack of understanding and the unsuitability of equipment integration held PCM to a minor role in the communications industry.

During and immediately following World War II, Bell Laboratories and the U.S. Army Electronics Command rekindled the interest in PCM, attempting to integrate this technique into existing transmission networks. Bell Laboratories designed and later produced a practical PCM system for tactical application by the Army. This exploitation marked the first time that PCM principles were translated into actual hardware.[4] The demand for multi-channel telephone capability was also occurring world-wide, and this proved to be an important impetus to PCM development.

What is the PCM technique? Compared to the previously mentioned voice coding techniques, it is slightly more complicated, requiring three successive steps to encode the input signal. The first step was to scan the voice signal and sample it at regular intervals as in PAM. This process was known as sampling. The second step was to associate each of these amplitudes with a predetermined discrete level. This was referred to as quantization. The last step was coding, where each quantized level was represented by a multi-bit code word, thus giving the signal its digital form.

Although Bell's patents for PCM were received in 1938 and 1942, the first disclosure of PCM to the public by Bell Laboratories was not made until 1947. Other landmark documents followed, notably by Shannon, Oliver, Pierce, and Reiling, who together, provided the theoretical background for modern sampling theory and the digital transmission techniques.[5,6] Internationally also, PCM was becoming better

understood, and so the opportunity for solid development was enhanced. Up to this point, physical restraints on hardware complexity hindered PCM's development into a marketable product, for economic rather than technological reasons. With the advent of the transistor and semiconductor era in the 1950's, system designers began re-evaluating their projects. The tools were then available to justify the attempt to manufacture the complex terminal equipment required. Additionally, the engineering community was improving its knowledge of digital devices. That resurgence of interest in PCM and digital transmission however, was short-lived for there remained two very good reasons why the manufacture of digital systems did not occur as might have been expected. There were large plant facilities, and massive central office equipment inventories to support analog transmission systems which could not be economically abandoned or altered. Furthermore, simultaneous advancements in analog techniques, such as improved filter technology and amplifier and cable construction, placed a question mark on the performance and economic advantages of changing to a digital-type system.

Various digital improvements followed, and soon after 1950, it was realized that various switching problems in electronic telephone exchanges could be simplified if the signals were in a digital form prior to entering the exchange. Advantages such as reduced power consumption, cost, and increased switching speeds, were among the strongest points in favor of digital transmission.[7] During this time frame, satellite communications

systems were also being engineered to provide a much needed compliment to the geographical coverage of existing High Frequency (HF) transmission, yet with more reliable services and with much greater channel capacity. Digital transmission was viewed as an important contribution to this developing technology. Experiments continued, and these were successful in advancing the state of the art in digital systems. Companding of the discrete levels was first explored about the time of Bell's disclosure on PCM. Companding greatly reduced the quantization noise (an inevitable result of the digitizing process) without consuming larger bandwidth. In early 1946, Delta Modulation (DM), developed in France, increased the voice handling capability of a transmission system by a factor of two for a given bandwidth, thereby increasing the overall bandwidth efficiency of transmission. DM digitized the slope, or amplitude difference, of the analog signal as compared to the previous sample, rather than its absolute value. If the slope remained constant, no pulse was transmitted. This is where the savings in bandwidth was most realized. An adaptive method of DM exploited the syllabic characteristics of speech to further reduce the bits required to accurately represent the signal. This method, known as Continuous Variable Slope Delta Modulation (CVSD), improved on DM by using a signal companding method to reduce the bandwidth requirement. CVSD was predictive in nature, using three consecutive pulses to predict the slope of the signal.[8] Improved coding techniques, based on modern information theory, expanded the amount

of information it is possible to transmit over a given channel. The number of such coding techniques are many, and will not be covered here. The reader is referred to the Error Protection Manual prepared for the Air Force Communication Service in April, 1973 for a detailed description of error coding techniques. It should be mentioned however, that well-designed coding techniques can and have improved the efficiency of transmitting voice signals over PCM and Delta Modulation schemes.

The first line-of-sight (LOS) terrestrial microwave systems were built in the 1950's as the main contender with coaxial cable for bulk transmission in long haul trunks for the telephone industry. The early systems utilized FDM-FM transmission techniques, operating below 10 GHz in the frequency spectrum. Later experiments were performed utilizing the digital transmission techniques, but the first digital system used three-level partial response signal coding with FDM-FM modulation.

While the technologies were developing, so was the need for an integrated military communications system. Prior to 1960, the military communication system was primarily a loose union of analog networks connected mostly by dedicated military transmission plant. The requirement for a joint communication effort among the services was becoming drastically apparent and, in 1960, the Defense Communication System (DCS) was formed within the Department of Defense (DOD). Its purpose was to be the single system which would handle all long-haul telecommunication requirements of the Department of Defense. In support of this

system, the Defense Communication Agency (DCA) was developed to exercise systems architecture, operational control, and supervision of the DCS.[9] Progress was slow initially, but major communication deficiencies during the 1962 Cuban Missile Crisis accelerated improvements of the DCS. An advance data transmission system project originated by the Air Force in 1958, known as Combat Logistics Network (COMLOGNET), came under management of the DCA in February, 1962. The name was later changed to AUTODIN (Automatic Digital Network) and became the world-wide military digital network for data.[10]

Concurrently in industry, manufacturing of digital equipment had become economically feasible, and advances in the modulation technology of PCM led American Telephone and Telegraph to begin development of their T1 (1.544 Megabits per second (Mbps)) carrier system in 1955. The Bell T1 carrier was first put into commercial application in Ohio in 1962. It was the first in their heirarchy of digital systems and was designed as an economic solution to short-haul, 10-50 miles, interoffice trunking of phone calls. The success of Bell's T1 system had established a foothold in digital transmission over cable carrier for commercial communication networks. This system was followed by T2 (6.312 Mbps), T3 (44.736 Mbps), and the T4 (274.176 Mbps) Digital Transmission System in 1975. The heirarchy had advanced from the 24 voice channels and 1.544 Mbps of the T1 system, to the 4032 voice channels and 274.176 Mbps of the long distance, coaxial cable T4 System which was designed to span the

continental United States.[11,12] The T2 system with its 6,312 Mbps was capable of transmitting a coded Picturephone signal, while the T4 system was capable of handling several commercial quality color TV signals.

PCM development progressed internationally along similar lines. Since 1961, the Japanese had been very active in PCM development for the short-haul application. The increasing demands and rapid growth of its telephone industry proved to be very influential in that endeavor. Its first successful field trials in PCM over wire pairs were completed in 1964. Japan's Nippon Electric Company (NEC) had a successful 24-channel digital microwave radio link in production stages in 1965.[13] This initial effort in digital microwave transmission proved to be a milestone in the development of digital transmission systems. Japan had also introduced a means to transmit digital data in a parallel, rather than in a serial format, as was previously done. This had the advantage of increasing the data rate, but at the cost of using more channels to permit the increased data rate.[14] Several other techniques were developed between 1963 and 1965. In 1963, a new companding technique by Reeves and Barber promised increased capability with simplicity of design using a digital companding coder. Binary coding techniques also continued to develop and improve the efficiency of handling increased data rates. In the United States, a log-differential method, similar to delta modulation, was developed. It was well-suited to the special waveform characteristics of speech. In operation, this form emphasized the higher frequency

components of speech, and used a log-law compander on the lower frequencies.[15] It was during this time period, February 1963, that Western Union placed the Automatic Digital Network (AUTODIN) into service for the Defense Communication Agency. Together with the Automatic Voice Network (AUTOVON) it comprised the DCS data and voice handling capability.[16,17]

Prior to 1965, the only PCM systems in actual commercial operation were Bell's 3000 T1 Systems in the United States. The PCM methodology used in these helped to overcome the noise and interference problems. The T1 system needed only to differentiate between three amplitude levels to maintain a high signal detection capability, permitting operation with a lower signal to noise ratio as compared to the analog systems. In contrast, FDM-FM analog systems must be responsive to a wide range of allowed signal levels requiring a higher signal to noise ratio. The use of digital transmission also helped to overcome the problem of cumulative noise effects in the longer transmission links. Regenerative repeaters, spaced approximately 6000 feet apart, accurately reshaped and reproduced the transmitted pulse train. In contrast, analog repeaters could not remove the noise accumulated distortion of the signal, but amplified the noise along with the desired signal.[18] The digital repeater can effectively remove the error-producing noise, and reconstruct a clean pulse signal with relatively low cost repeater design. This does however, require precise timing and synchronization between transmitter, repeater, and receiver.

To this point in time, digital transmission growth had followed the profile of an irregular-shaped staircase. There were periods of significant progress, and there were periods of apparent stagnation. The theory and principles of digital transmission had been developed, applications were proven feasible, but something was needed to put digital transmission on the market on a large scale. The motivations for going digital were steadily growing. A data explosion was occurring. Large scale digital data handling and the use of computers were becoming widespread.[19] The resultant increase in the generated digital form of data added a new dimension to the communications market. Advances in Large Scale Integration (LSI) technologies provided advantages in price and performance in components needed for digital transmission. The components required for the high speed, complex processes of sampling, quantizing and coding were then economically available. LSI helped to open the door for marketing, but it was not the panacea. Not all problems of digital transmission integration could be solved by this method. Some communication systems, for example, do not require sufficient volume of equipment to economically justify LSI. The LSI technology did, however, allow an economic advantage in producing the complex logic circuits and the introduction of microprocessors into the digital transmission system. The Military was using more facsimile, more digital data transmission, and other similar forms of communications than was industry.[20] It had established a requirement not only to handle the

increased data, but also to secure its communications. It was to that end that the Military began to seriously investigate currently available digital equipment.

The close of the 1960's found industry and the Military in a position of increased interest, and showed industry to be moving in a more confident manner with respect to digital transmission. Industry was anticipating the move toward digital systems, and in November 1969, Data Transmission Company (DATRAN) filed an application with the Federal Communications Commission (FCC) for construction permits for 244 microwave repeaters and terminal equipments for their proposed all digital, data transmission network.[21,22] That was the first filing of its kind with the FCC, and that pioneering effort by Datran as a specialized carrier began to open up the industry in terms of digital transmission application. This was to be a motivating force for further developments in digital microwave technology, an area the Military was seriously contemplating. In their proposal, Datran compared domestic satellite, analog transmission, microwave radio, and a cable carrier system as the mode of transmission for this digital data backbone system. Since domestic satellite with digital transmission capability would not be deployed at the time of Datran's system design, it was not included for analysis. Cable carrier and microwave were thoroughly compared, and in the final analysis, the decision was to build their system on digital microwave transmission technology.[23] The decision was based on the proven

reliability of FM microwave, the economics of construction, the ability to traverse all types of terrain, and the time and ease of implementation as compared to cable installation. Many queries from industry to the FCC followed, and soon an important question emerged from the increased level of activity in digital transmission systems regarding interference with operating analog systems. The FCC, in response to regulatory questions being raised by the various competitors, released on September 15, 1971, Docket No. 19311 Notice of Inquiry which was concerned with the use of digital microwave radio and its affect on existing analog systems.[24] Decisions on policy had to wait, however, while extensive studies on interference of proposed digital transmission with current FDM Analog systems were carried out. At that time, only American Telephone and Telegraph and Microwave Communication Incorporated operated digital microwave systems. However, in November 1971, Raytheon Data Systems established their RDS-80 Digital Microwave Transmission Link between Albany and Troy, New York for the New York Telephone Company.

In early 1971, the military was seriously considering digital transmission in response to the secure communications requirements of the DCS.[25] The initial proposals consisted of a pilot program employing the digital microwave technology in a system upgrade from analog to digital. Lacking the in-depth knowledge and familiarization with digital transmission equipment, the Military began planning the introduction of

digital sub-systems into the DCS with the help of industry. The solution appeared to be bulk encryption of all digital traffic, and in this effort, the Military cohesively began the development of a time phased test program to test and evaluate available digital transmission equipment. Due to the nondiscrete nature of analog signals and systems, it was felt that an analog signal could not economically be encrypted. The decision to begin testing led to the organization of several military digital tests. A PCM/TDM System Design Verification Test Program was conducted by the Defense Communications Engineering Office (DCEO) and the National Security Agency (NSA) from July 15, 1971 until January 1, 1972. The test program also included the investigation of performance assessment and fault isolation techniques[26,27] of digital microwave fixed plant, point-to-point systems. The results of this test and other military testing in response to the desired usage of digital transmission will be covered in detail in Chapter Six. Another significant event occurred during this time. In February 1971, the Deputy Secretary of Defense established the Tri-Tac Office under DOD Directive 5148.7. Its purpose was to supply a joint service effort in all tactical communications control facilities and communications security. The test and evaluation plan of the DCS was growing steadily with strong emphasis placed on the military services cooperation in joint development efforts.

Having established its plan for digital transmission in the DCS, the Military and industry collaborated in an effort to explore the possibilities

of using existing analog radios for efficient transmission of digital data. This was a driving force, since this method utilized existing plant, and off-the-shelf equipment, eliminating extensive and costly design and test periods. Additionally, modulation studies during the late 1960's led to developments of frequency and phase shift keying modulation methods. Forms of the latter were felt to provide the optimum tradeoff of bandwidth reduction, and the sensitivity to noise and co-channel interference.[28] For the FM radio, multi-level partial response baseband signals were considered the solution for signal processing and transmission of digital data over an analog system. The technical aspects of these techniques will be discussed in Chapter Three; however, it is important to mention that these digital modulation techniques greatly improved the spectrum efficiency of the evolving digital transmission technology. The initial tests were designed to provide the stepping stones for transition to an eventual all-digital system.

While these developments continued, industry responded to Docket No. 19311. On May 8, 1973, the FCC released a notice of proposed rule-making clearly delineating the various modulation techniques, adding pulse modulation to the list, and stated how associated digital equipment should comply with respect to RF bandwidth, number of voice channels, and emission standards.[29,30] A main consideration in the FCC's "proposed rule-making" was that this new technology must work in the same geographic areas, and be compatible with existing analog systems.

To bring the history of digital transmission up to the present date, the major improvements to the basic system during the 1970's will be discussed. To this point, the history of voice digitization and digital transmission has been traced, the basic technologies of the various systems have been developed, and the regulatory response of the government to Docket No. 19311 has been capsulated. The period of 1971-1977 produced even greater advances in the digital transmission system design. It was determined through the FCC Inquiry that the interference problem of PCM with FDM could be reduced by such methods as direction coordination between PCM and FDM links, since the interference effect can be reduced if the direction of transmission is the same for both modes.[31] Cable Test Procedures have also been improved to facilitate testing in both directions, as well as testing the entire system from a single location. Technology in fault location allowed expansion of the length on the long-haul lines by patching faulty spans of the line, and testing individual repeaters for failure. However, phase jitter proved to be a limiting factor in an extended PCM/TDM line. Phase jitter is an abrupt change or variation caused by impulse noise, interference from other systems, or pulse pattern changes in the transmitted bit stream.[32] Since the timing reference is normally retrieved from the pulse stream, the effects of phase can be controlled if the clock timing pulses follow the pulse pattern changes, and sampling occurs at the center of the incoming pulses.[33,34] Earlier, equalization helped solve the problem

in analog transmission systems of unequal attenuation of the frequency range. Today, in the world of high-speed data transmission, equalizers are used to introduce a controlled amount of delay to achieve uniformity over the entire bandwidth providing an increased linear response of the system. This was accomplished by using an adjustable filter to compensate for interference caused by non-uniform delay.[35,36]

CVSD, in development stages during the last decade, became a reality, having completed testing and production stages for voice channel encoding. This coding method realized gains in bandwidth of up to 4:1, with still greater savings a distinct possibility. Linear Predictive Coding eliminated redundancy by subtracting that part of the signal which can be predicted from its past,[37] however; this, together with CVSD, was designed specifically for voice signal and not high speed data. Similar in design, Differential Pulse Code Modulation (DPCM), in its simplest form, transmitted only the difference in signal strength from the previous sample removing some of the redundancy. Adaptive DPCM however, was more complex and used adaptive, or automatic quantizers to predict short-term changes in the spectrum of speech as well as the changes in signal amplitude.[38] As the methods for preparing signals for digital transmission evolved, so had the methods of transmission. Satellites, millimeter waveguides, and fiber optics have entered the telecommunications inventory. Transmission at frequencies of 10^{15} Hertz in the visible light spectrum are possible. The higher frequency technologies provide

greatly increased bandwidth which could handle increased data rates, if required. The reduced energy requirements for operation of digital repeaters lends itself to another developing technology, that of solar energy. These RF repeaters, like communications satellites, can be powered by a bank of solar cells by day, and by rechargeable batteries at night.[39] Technological breakthroughs, such as solar energy, strengthen the motivations toward digital transmission. Complex digital coding techniques and high-level multiplexing have also greatly improved the efficiency of communication systems. Future systems will not be lacking in the control logic of digital devices so essential to complex, high-speed transmission of data.

The initial systems architectural work accomplished by the Defense Department Agencies in seeking to introduce digital transmission into the DCS was a cooperative effort with the Department of Commerce, Institute of Telecommunications Sciences (ITS), Boulder, Colorado. Digital test bed experiments at Richards Gebaur Air Force Base (Air Force Communications Service), Fort Huachuca (Army Communications Command), and the Rome Air Development Center in New York led to the implementation of the following upgrade programs with significant ITS contributions. The first fixed plant, point-to-point military digital microwave system to become operational was the Frankfurt-Koenigstuhl-Vaihingen System (FKV) upgrade program in 1975 in the Federal Republic of Germany. The FKV Upgrade was the initial project of the U.S. Army Communications

Command's modernization of the European Wide Band Communications System (EWCS) to provide long-haul secure digital Communications.[40]

In April, 1976, Stage I of the Digital European Backbone (DEB) Terrestrial Subsystem Upgrade Project by the U.S. Air Force began the conversion of the DCS mainline route from the conventional analog transmission to digital transmission. The four stage program will incrementally transition the DCS to a predominantly digital transmission system providing the essential bulk encryption of the DCS links. DEB will interconnect with the U.S. Army's FKV System at Vaihingen, Germany, with Stage I completion scheduled for March, 1978.[41] Follow-on stages will incorporate tributary digital links connecting Germany with Belgium and the United Kingdom using PCM/TDM technologies.

Although both the FKV System and DEB Stage I utilize the three-level partial response modulation technique, the succeeding stages will incorporate pure digital technologies such as Quarternary Phase Shift Keying (QPSK). The question then, is not whether the military should convert its communication system to digital transmission, but rather, how to accomplish the transition effectively and economically.

Motivations for Digital Transmission

The historical overview has highlighted some of the major events and motivations which have developed and molded the digital transmission technology of today. The motivations which have driven the state of the art are restated here for emphasis, to include the military development

of digital transmission in the Defense Communications System.

Advances in manufacturing of digital transmission components brought about by MSI, LSI, and MOS techniques have provided the economic motivation for digital transmission. The advantages become even more significant when switching, multiplexing, and other peripheral equipments are brought into the picture. Interface problems have become less complex by removing the Analog to Digital and Digital to Analog Converters. The digital transmission technology has shown a realization for the reduction in long-term O & M costs. The requirement for handling the many digital format signals has grown to be a strong motivating factor. Digital transmission includes video signals from radar scopes and television screens as well as high-speed data and digitized voice. Examples of these are the information transmitted to control centers from air traffic surveillance radars, the data relayed from remote environmental sensors, or television program distribution systems.[42] The motivations for transitioning to a digital transmission system are many, but the main reasons for the military decision to employ digital techniques in all future communications system upgrades are the need for bulk encryption to maintain communications security, the flexibility to accomodate increased data requirements, and the interoperability with digital tactical communications systems and digital subsystems such as between switching and transmission. The DCS decision for digital upgrade includes all subsystems for satellite, terrestrial, and leased

transmission subsystems, and encompasses the integration of the essential Defense Satellite Communication System (DSCS) into the DCS.

Transmission systems using digital techniques can be engineered in any number of ways, depending on user requirements. In this light, some of the most promising and most studied technologies for digital transmission will be discussed, and a comparison of these technologies is made in the following chapter.

CHAPTER 2

Footnotes

1. M.D. Fagen. A History of Engineering and Science in the Bell System. Holmdel, Bell Telephone Laboratories, Inc., 1975, p. 326.

2. E. Maurice Deloraine and Alec H. Reeves. "The 25th Anniversary of Pulse Code Modulation." IEEE Spectrum. Vol. 2, No. 5 (May, 1965), p. 57.

3. Ibid., p. 57.

4. Ibid., p. 58.

5. Ibid., p. 58.

6. B.M. Oliver., J.R. Pierce, and C.E. Shannon. "Philosophy of PCM." Proceedings of the IRE. Vol. 36 (November, 1948), pp. 1324-1331.

7. Ibid., p. 59.

8. National Security Agency, Communications Security Organization. Continuous Variable Slope Delta Modulation. May, 1973, p. 4-7.

9. R. H.Levine. "The Evolving DCS: Introduction and Overview." Conference Record, 1976 International Conference on Communications. Vol. II, June 14-16, 1976. Philadelphia, pp. 33-2.

10. Donald A. Hamsher. Communication System Engineering Handbook. St. Louis, McGraw-Hill Book Company, 1967, p. 12-22.

11. N. Knapp and N.E. Snow. "Digital Data System: System Overview." Bell System Technical Journal. Vol. 54, No. 5 (May-June, 1975), p. 832.

12. James Martin. Telecommunications and the Computer. Second Edition. Englewood Cliffs. Prentice-Hall, Inc., 1976, pp. 248-250.

13. "Microwave PCM System." Nippon Electric Company, Limited. Sales Brochure. Cat. No. 317-4-2-E, 7004-2000M. Japan.

14. E. Maurice Deloraine and Alec H. Reeves. "The 25th Anniversary of Pulse Code Modulation." IEEE Spectrum. Vol. 2, No. 5 (May, 1965), p. 59.

15. Ibid., p. 60.

16. Albert P. Broglie, Seymour Krevsky, and Leo H. Wagner. "The Global Digitally Switched Communications Systems Evolution." Symposium on Computer-Communications Networks and Teletraffic, Polytechnic Institute of Brooklyn, April 4-6, 1972, pp. 549-551.

17. Donald H. Hamsher. Communication System Engineering Handbook. St. Louis, McGraw-Hill Book Company, 1967, p. 12-22—12-25.

18. "Heterodyne Repeaters for Microwave." The Lenkurt Demodulator. Vol. 13, No. 8 (August, 1964), p. 1.

19. "Satellite-Computers-Communications." Telecommunications. October, 1976, p. 15.

20. "Military Versus Commercial Carrier Design." The Lenkurt Demodulator. Vol. 10, No. 4 (April, 1961), p. 131.

21. Allen P. Worley. "The Datran System." Proceedings of the IEEE. Vol. 60, No. 11 (November, 1972), p. 1357.

22. Gene Bylinsky. "Datran's Hazardous High-Wire Act." Fortune. February, 1976, p. 133.

23. Worley, op. cit., p. 1359.

24. The Federal Communications Commission. Docket No. 19311, Notice of Inquiry. Adopted: September 8, 1971; Released: September 15, 1971.

25. Defense Communication Engineering Office. Application of Pulse Code Modulation (PCM) Time Division Multiplexing (TDM) and Digital Transmission in the DCS. January 7, 1975, p.1.

26. Defense Communications Engineering Office. Preliminary Report: PCM/TDM System Design Verification Test Program. February 25, 1972, pp. 1-1—1-2.

27. I.P. Plotkin. "The Performance Monitor Problem for a Digital DCS." National Telecommunications Conference. Atlanta. Vol. I, November 26-28, 1973, p. 4B-1.

28. Avantek, Comments. Docket No. 19311, Notice of Inquiry. Adopted: September 8, 1971; Released: September 15, 1971.

29. The Federal Communications Commission. Docket No. 19311, Notice of Proposed Rule Making. Adopted: May 3, 1973; Released: May 8, 1973.

30. R.C. DeWitt. "Digital Microwave Radio." Telecommunications. April, 1975, pp. 30-31.

31. "PCM-FDM Compatibility Part 1." GTE Lenkurt Demodulator. July, 1971, p. 3.

32. "Extended Length PCM Systems." GTE Lenkurt Demodulator. February, 1974, pp. 2-3.

33. Ibid., p. 2.

34. "Data Transmission: Principles and Problems." GTE Lenkurt Demodulator. August, 1974, p. 5.

35. Erling D. Sunde. Communication Systems Engineering Theory. New York, John Wiley & Sons, Inc., 1969, pp. 184-186.

36. W.G. Chaney. "Equalization of Telephone Lines for Data Transmission." Electronic Communicator. May-June, 1968, p. 4 and p. 7.

37. B.S. Atal and M.R. Schroeder. "Adaptive Predictive Coding of Speech Signals." Bell System Technical Journal. Vol. 49 (October, 1970), pp. 1973-1975.

38. Nuggehally S. Jayant. "Digital Coding of Speech Wave Forms: PCM, DPCM, and DM Quantizers." Proceedings of the IEEE. May, 1974, p. 619.

39. "Increasing PCM Span-Line Capacity." GTE Lenkurt Demodulator. May/June, 1976, pp. 17-18.

40. Department of Defense, Electromagnetic Compatibility Analysis Center Technical Report No. ESD-TR-73-012. EMC Analysis of the DCS Frankfurt-Koenigstuhl-Vaihingen Upgrade. May, 1973, p. 1-1.

41. Electronic Systems Division, Air Force Systems Command. Digital European Backbone (DEB) Program. Program Management and Implementation Installation Plan (PMI/IP). 16 May 1977, p. 1.

42. Albrecht P. Barsis. A Proposed Five-Year Plan in Radio Communications Systems Performance at Frequencies Between 10 and 30 GHz. FY 1975-1979. U.S. Department of Commerce. May, 1974, p. 28.

CHAPTER 3

DIGITAL TRANSMISSION TECHNOLOGIES (MODULATION TECHNIQUES)

Consistent with the growing demands for data communications, developments have been made in the techniques of digital modulation which have increased the efficiency with which a transmission system uses the radio frequency spectrum, and how insensitive it is to disturbances. Modulation as used here is defined as the process of altering some characteristic of a carrier signal in accordance with the instantaneous value of an information signal. A radio carrier can be modulated in amplitude, frequency, or phase, or in any combination of these characteristics. The optimum digital modulation technique depends on many factors, such as the type of noise or interference which may be encountered, and the type of transmission (i.e., microwave, cable, or satellite) to be used.

This chapter describes the digital microwave modulation techniques. A block diagram showing the principal components of a communication system, including the modulation process is shown in Figure 3-1.

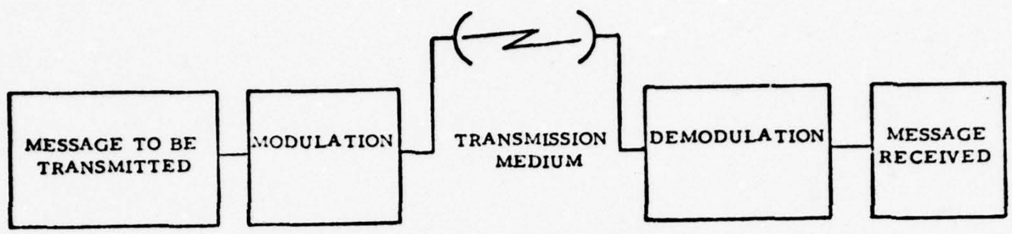


Figure 3-1. Fundamental Communication System

The occupied spectrum of a microwave carrier with reference to the total bit rate is a primary concern in modulation analysis. This parameter, referred to as RF spectrum efficiency measured in bits per hertz, is dependent on the type of modulation, as well as the degree of RF spectrum filtering used.[1] According to Shannon's fundamental theorem of information theory, the bits per Hertz must always be less than or equal to $\ln_2 (1 + S/N)$. Generally, complex modulation formats and more severe filtering techniques reduce the occupied spectrum, but with resultant increases in complexity and costs. Generally, complex modulation formats and more severe filtering techniques reduce the occupied spectrum, but with resultant increases in complexity and costs, and a decrease in receiver threshold.

The basic digital data signal is a coded stream of pulses representing the information to be transmitted. One of the modulation techniques for data transmission is Amplitude Shift Keying (ASK) which in its simplest form, uses the presence or absence of a carrier to represent the

two information states (1, 0). A more common method of digital modulation is Frequency Shift Keying (FSK) which uses two or more discrete frequencies to represent the information states. A third method of digital modulation is Phase Shift Keying (PSK) in which the carrier phase is changed to represent the information states. This is generally a more efficient technique than ASK or FSK, and is often used in systems having a large channel capacity. The first large scale deployment of digital microwave radios was based on using a 3-level partial response digital signal, driving a conventional FM radio. (The 3-level signal is produced by low-pass filtering a non-return-to-zero bit stream at one-half the clock rate.) This modulation technique utilized existing FM radio systems, and improved the spectral efficiency of Binary ASK, FSK, and PSK, but was still only an interim solution to the increasing demands for digital transmission. More complex techniques, such as multi-level Phase Shift Keying and Quadrature Partial Response Signalling were being developed and tested for future application in digital transmission systems. The following section is a descriptive and comparative analysis of nine most commonly used modulation techniques.

Analysis Criteria for Comparison of Techniques

In analyzing the various modulation techniques utilized in digital radio systems, the bit error rate (BER) performance for a specified signal to noise ratio is a major figure of merit, much the same as the noise power ratio (NPR) is a figure of merit for an FDM-FM system.

Table 3-1 compares the spectral efficiency in bits per Hertz, with respect to the required Signal to Noise Ratio (SNR) for a constant bandwidth and BER. The BER performance in the presence of random noise is also a valid means of comparing system's performance, but is not treated here. Power efficiency, or the transmitted power per bit, is also provided with respect to Quadriphase Shift Keying (QPSK). It is important to note that Table 3-1 shows the relative power efficiency of BPSK equal to that of QPSK. This is true because BPSK requires half the SNR of QPSK, and also, has only half the spectral efficiency; therefore, the relative power efficiency of BPSK does equal that of QPSK.

The spectral efficiency in bits per Hertz can be determined in several ways, as noted below.

> A unit of measure of the efficiency of various modulation schemes is the term bits-per-hertz of occupied spectrum. One of the problems in using this term is the definition of occupied bandwidth. The theoretical narrow limit is the Nyquist bandwidth, or approximately 3 db bandwidth. This bandwidth gives the most favorable number and is usually what is stated in texts when modulation methods are compared.... The 99 percent power bandwidth is sometimes used to define the spectrum. This percentage gives a slightly lower number.... [2]

Amplitude Shift Keying (ASK)

In Amplitude Shift Keying, the carrier is pulsed with the digital bit stream so that the presence of the carrier represents a binary "1" or "mark", and the absence of the carrier represents a "0" or "space" as shown in Figure 3-2.

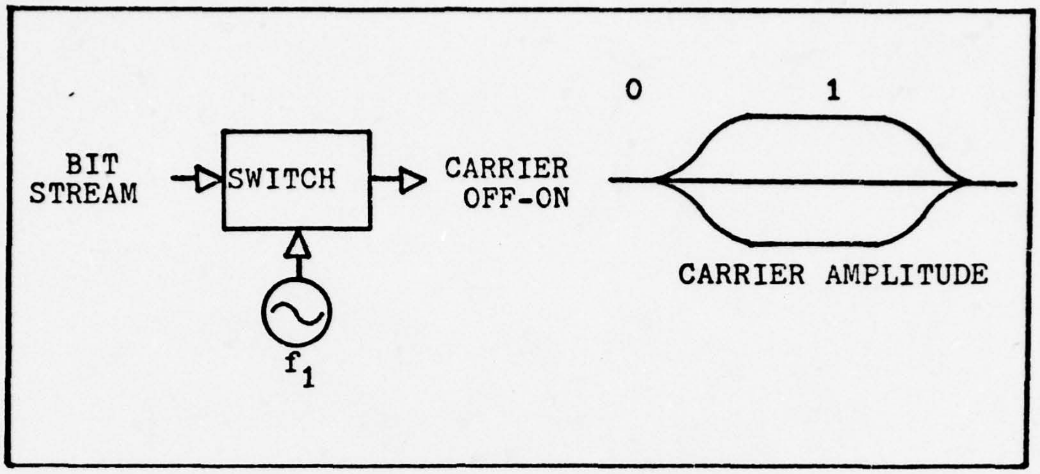


Figure 3-2. Amplitude Shift Keying

Binasy ASK for example, utilizes two logic levels, and the RF bandwidth consumed is up to twice the bit rate. A particular binary ASK modulation scheme requires a signal to noise ratio (SNR) of 14.4 dB in a fixed bandwidth to provide a BER of 10^{-4}. It requires more power than QPSK (transmitted power per bit), and has a spectral efficiency of 1 bit per hertz.[3,4] The relatively inefficient use of bandwidth, and the techniques dependence on amplitude linearity for accurate signal detection have restricted ASK modulation to limited usage.

Frequency Shift Keying (FSK)

A binary FSK signal is characterized by the carrier assuming either of two discrete frequencies; frequency f_1 representing a binary "0", and frequency f_2 representing a "1". Reference Figure 3-3. Binary FSK utilizes two logic levels as does binary ASK, and consumes RF bandwidth equal to twice the bit rate. For a fixed bandwidth, and a

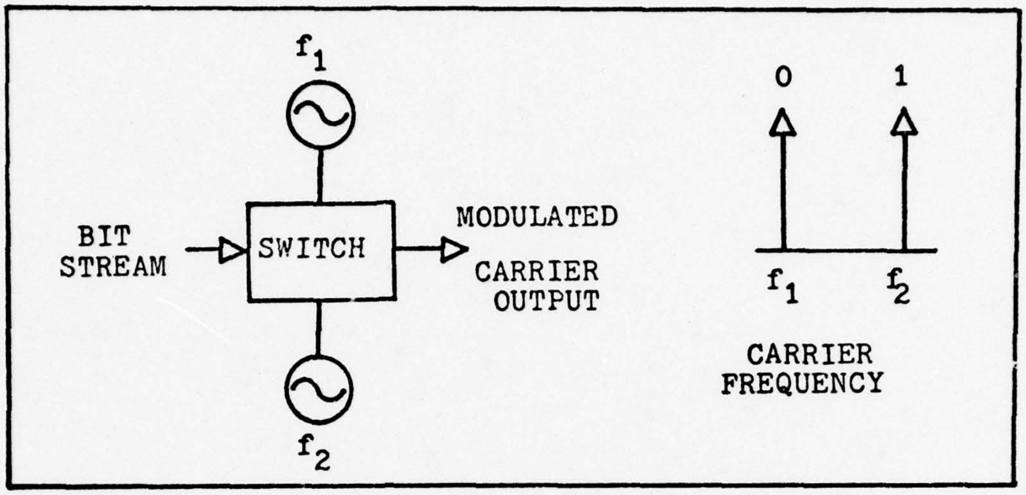
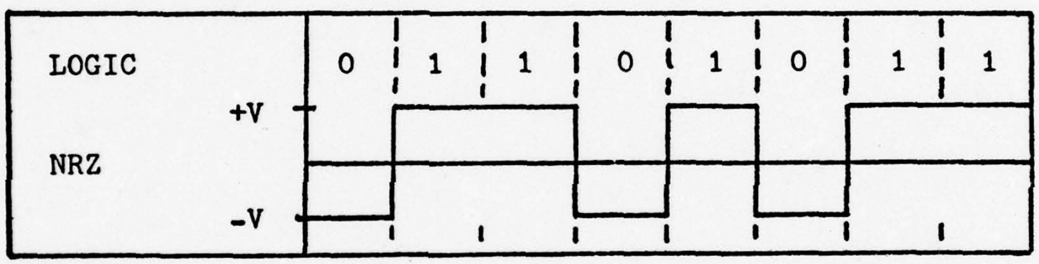


Figure 3-3. Frequency Shift Keying

derived BER of 10^{-4}, FSK requires a SNR of 11.7 dB. It too is less power efficient than QPSK, but more efficient than ASK, and provides a 1 bit per hertz spectral efficiency.[5] Binary FSK and ASK are both inefficient in bandwidth usage, but FSK is not as dependent on amplitude linearity for signal detection. This insensitivity to amplitude changes provides greater tolerance to signal fading, impulse noise, and other amplitude disturbances. The frequency modulated signal has information-bearing sidebands which must be transmitted for accurate signal detection. A special form of FSK with a modulation index of 0.5 utilizes a frequency equal to one-half the bit rate, and an RF bandwidth equal to one and one-half times the bit rate.[6] Collins Radio refers to this modulation technique as Minimum Shift Keying (MSK).[7] MSK concentrates energy in the sidebands to reduce the effects of adjacent RF channel interference, but at the cost of RF bandwidth. An FSK technique was used by DATRAN for its coast-to-coast digital data system.

Partial Response Signalling (Three-level Partial Response)

This modulation technique was selected for use by the Army to meet its interim digital transmission requirement for upgrading the FKV System. The VICOM three-level partial response waveform is produced through the use of two low-pass filters, one before, and one after the transmission medium. (Reference footnote 8). Three-level partial response starts with a Non-return-to-zero (NRZ) bit stream as shown below.



Each NRZ pulse produces an output pulse with amplitude equal to one-half of the NRZ amplitude, but having a pulse duration equal to twice the NRZ period. Reference Figure 3-4, Three-level Partial Response, for a pictorial representation of the partial response filtering technique. This method treats any NRZ pulse input as a superposition of individual 1-bit pulses, and then sums the 1-bit responses into one of three levels as shown in Figure 3-4 . After transmission, this input to the decoder is sampled, and reconstructs the original NRZ bit stream based on which of the three possible levels the waveform takes at the time of sampling and the recent history of the reconstructed data stream. The following three rules are used to derive the NRZ stream.

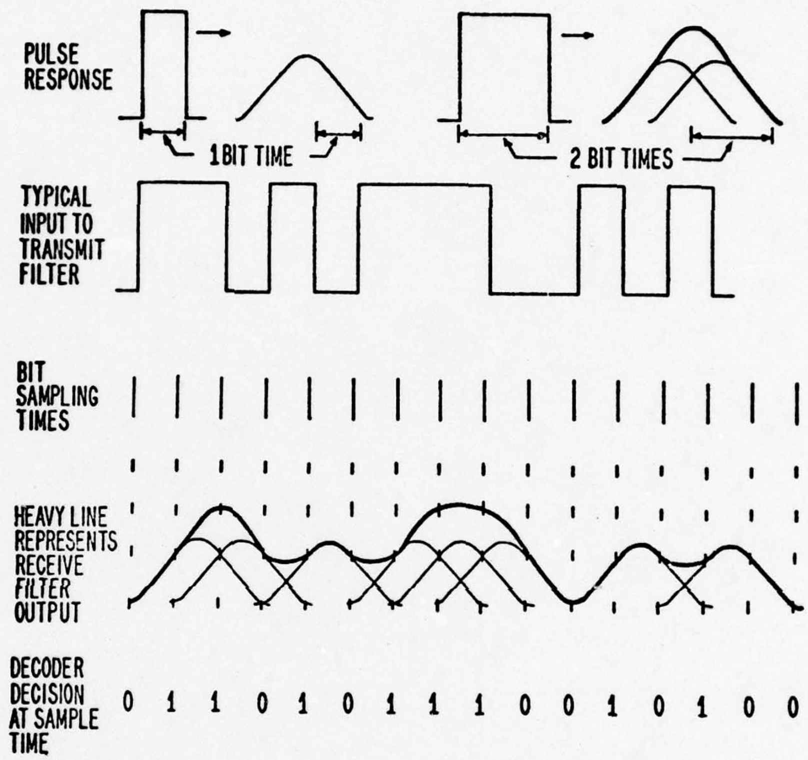


Figure 3-4. Three-level Partial Response

(Source: VICOM, PSB-6004, Digital Multiplexer Description, Operation and Theory of Operation, p. 3-11, Figure 3-11.)

The NRZ output is 0 if the partial response waveform was at a negative peak.

The NRZ output is 1 if the partial response waveform was at a positive peak.

The NRZ output is the opposite of the preceding NRZ bit if the partial response waveform was at center level.[8]

This modulation technique has a theoretical upper limit of 2 bits per hertz spectral efficiency, and requires a SNR of 7.5 dB above that of QPSK for a BER of 10^{-4}.[9] It consumes bandwidth equal to approximately

the bit rate. An advantage of the partial response technique is that it is possible to check for transmission bit errors, since only certain transitions are possible in an error-free partial response waveform,[10] for example, a positive peak at one bit time, may not be followed by a negative peak at the next bit time. The partial response technique has developed into 4-level, 7-level, and 8-level formats. This summation process however, requires a more complex signal compression process, with a resultant increase in the SNR to achieve the BER performance. For example, 7-level partial response would further reduce the 3-level bandwidth by an approximate factor of two using compression techniques. Generally, this costs about 6 dB in terms of SNR.[11] This modulation technique was chosen by the Bell System to place a 1.544 megabits per second T-1 line in the lower 400 KHz of a microwave baseband, and is often referred to as Data Under Voice (DUV).

Binary Phase Shift Keying (BPSK)

The simplest of the phase modulation techniques, BPSK shifts the phase of the carrier 180 degrees according to the binary state of the baseband signal. (Figure 3-5.) This technique utilizes two logic levels, and consumes an RF bandwidth equal to twice the bit rate. For a fixed bandwidth, and BER equal to 10^{-4}, BPSK requires a SNR of only 8.4 dB, the lowest of the modulation techniques analyzed. The theoretical limit for spectral efficiency is 1 bit per hertz of modulated RF signal.[12] Binary phase shift is highly tolerable to noise and interference, but

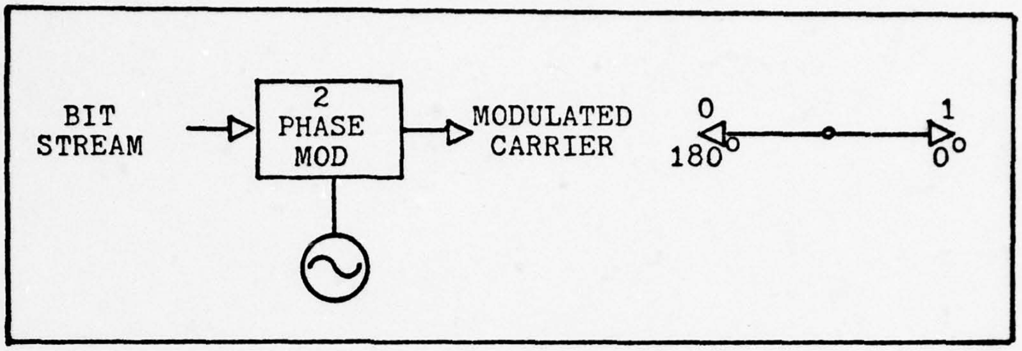
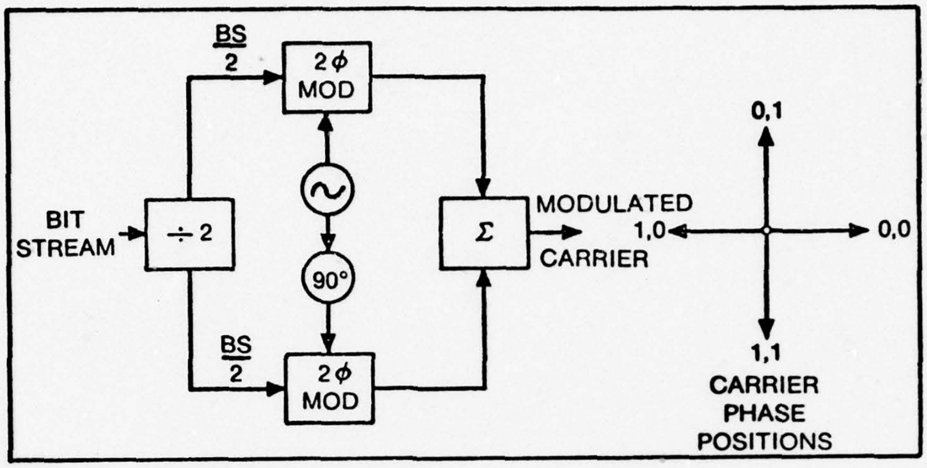


Figure 3-5. Binary Phase Shift Keying

costly in bandwidth consumption. BPSK is widely used in current digital systems for satellite communications, such as Westar and RCA Satcom. In practical digital systems however, it may be necessary to band-limit the transmitted spectrum due to possible restrictions on the available bandwidth. Higher order modulation techniques are viewed as a method to satisfy this requirement.

<u>Quadraphase Shift Keying (QPSK)</u>

As a general rule, phase modulated carriers perform best in the presence of random noise when compared to amplitude and frequency shift keying. Theoretically, QPSK provides the best solution among multi-level shift techniques when threshold performance, and complexity of design are important. QPSK modulation utilizes four logic levels, and can attain a spectral efficiency of 2 bits per Hertz. It requires one half the bandwidth of BPSK, and operates effectively with a SNR of 11.4 dB for a BER of 10^{-4} [13] (3dB over BPSK). Reference Figure 3-6.



- HAS BEST NOISE-EFFICIENCY PERFORMANCE
- 4-LOGIC LEVEL SYSTEM

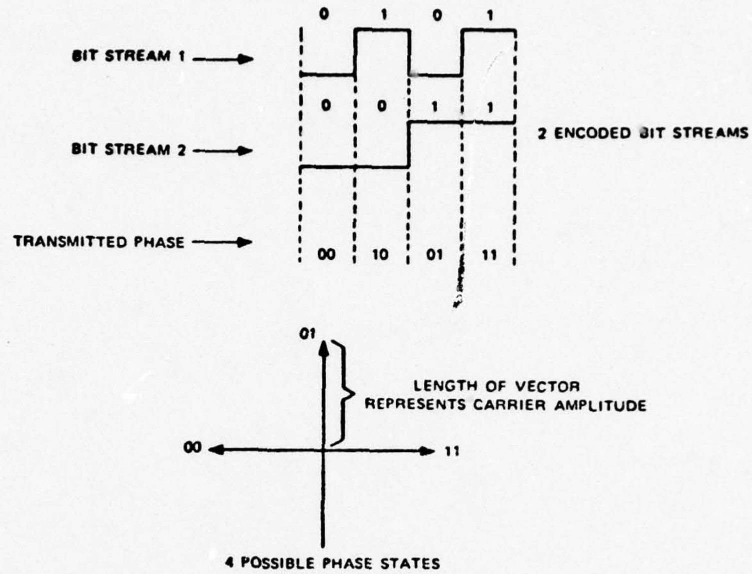
Figure 3-6. Four Phase Shift Keying

(Source: "Digital Microwave Transmission Symposium." Rockwell International, Collins Commercial Telecommunications Division, April 18-21, 1977, Dallas, Texas, p. 3-24, Figure 25.)

The incoming bit stream on Figure 3-6 is divided into two bit streams, each at half the original bit rate. The bit streams then drive a 4-phase modulator producing the QPSK signal. QPSK is a power efficient technique, particularly when compared with an FM System.

The multi-level phase modulation techniques (4, 8, 16-level), although more efficient in bandwidth utilization, require a tradeoff in threshold performance in distinguishing the phase states.[14] Figure 3-7 illustrates the QPSK technique.

The higher level systems have increased vulnerability to noise and interference. This is accountable to the fact that the individual states are more difficult to distinguish.



Detection of QPSK requires that the original carrier phase be recovered; here again the QPSK signal can be multipled to remove phase ambiguity and recover the carrier. The receiver has 2-phase comparators working in quadrature, each detecting 2 of the possible 4 phases. As can be seen from the following vector diagram, when the carrier is recovered and compared with the QPSK signal there is an effective 3 dB loss in carrier power. The carrier must be shifted 45 degrees to have maximum detection efficiency for all received phases. There is a degradation of 3 dB in theoretical carrier-to-noise as compared with PSK, assuming the same Nyquist bandwidth. However, the bandwidth can be reduced to one-half that of PSK due to baud rate being 1/2 bit rate, resulting in the same threshold as PSK.

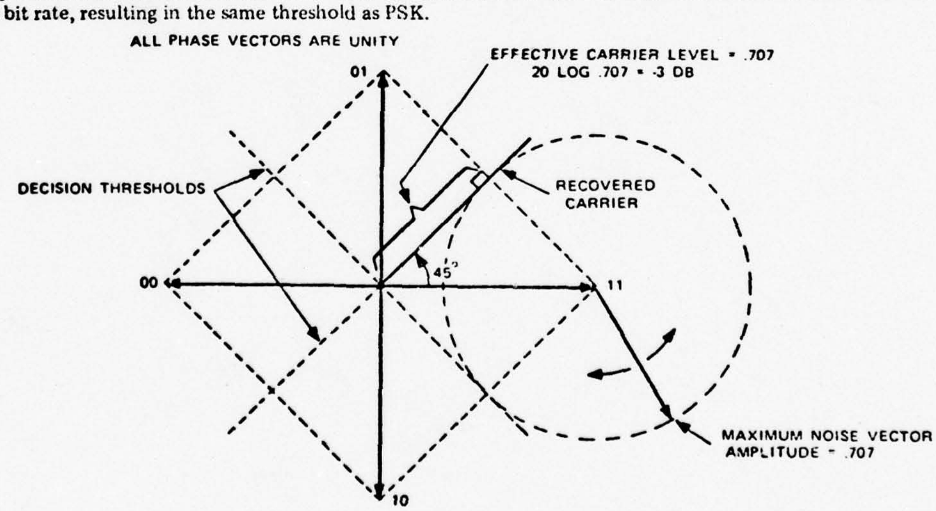


Figure 3-7. Phase Generation and Phasor Representation of QPSK Signal

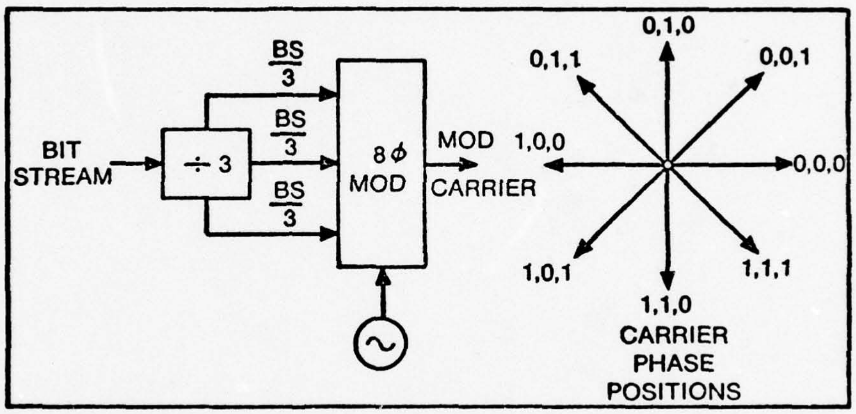
(Source: Collins MDR-11/DMX-13 Microwave Digital Radio System Product Description, p. 27.)

The conventional four-phase modulation however, is attractive for the microwave bands above 10 GHz. QPSK offers the optimum trade-off of bandwidth and bit error performance, and provides relative ease in accomplishing the four-phase modulation and demodulation process. Four-phase modulation with coherent or differentially coherent detection (refer to section on QPRS Modulation for definition of detection methods) is considered the most suitable for large capacity radio-relay systems with digital signal transmission rates of 100 Mbps or more.[15] When bit rates exceed 100 Mbps, the transmission of high definition television signals is possible.

The versatile QPSK has found several applications in transmission systems today. It is utilized in many terrestrial microwave, and satellite communications systems, such as Telsat, Intelsat, and Satellite Business Systems (SBS). Additionally, a development by Dr. James S. Gray of Radiation Systems Division combined two quadrature 1.5 GHz carriers which were bi-phase modulated, to provide a 1 Gigabit per second data rate.[16]

Eight-phase Shift Keying (8-PSK)

8-PSK is technically derived from QPSK using the same basic technology, with a further reduction in the transmitted RF spectrum. To accomplish this, the data stream is divided into three bit streams, each at one-third the original bit rate, which in turn drive the 8-phase modulator (Figure 3-8).



- USED BY COLLINS IN MDR-11 EQUIPMENT
- 8-LOGIC LEVEL SYSTEM

Figure 3-8. Eight Phase Shift Keying

(Source: "Digital Microwave Transmission Engineering Symposium," Rockwell International, Collins Commercial Telecommunications Division, p. 3-25, Figure 26.)

The 8-PSK detection process is more complex due to the increased number of phase states, and is more susceptible to the effects of noise. Since the data stream is split into three bit streams, it is theoretically possible to obtain a spectral efficiency of 3 bits per hertz, if optimum filtering is used. One particular 8-phase technique requires a SNR of 16.5 dB for a given bandwidth and a BER of 10^{-4}.[17] The RF bandwidth consumed

is one-third that of BPSK, or equal to two-thirds the bit rate. This technique provides an important advantage since 90 Mbps of data can be handled within 40 MHz of the spectrum which is the FCC allocation for carrier frequencies above 10 GHz.[18] QPSK with cross-polarization (two radios on the same frequency with respective vertical and horizontal feeds) provides a similar capability, but with the growing popularity of 8-PSK, QPSK equipment designed for that specification may not be available for future add-on.[19] 8-PSK has found application in many terrestrial radio relay systems and in Intelsat Time Division Multiple Access (TDMA).

Sixteen-Phase Shift Keying (16-PSK)

Much the same discussion is relevant to 16-PSK as was to 8-PSK and QPSK. The 16 logic level technique provides a further reduction in transmitted RF bandwidth to one-half the bit rate. Figure 3-9 shows the basic keying modulation scheme. Although 16-PSK has the potential for a Nyquist limit of 4 bits per hertz spectral efficiency, this technique requires a carrier to noise ratio four times as large as 8-PSK, (that is, a 22.1 dB ratio of signal to noise) for a given BER and bandwidth. Systems employing high-level modulation schemes such as 16-PSK become very complex to implement and some sacrifice in threshold performance must be expected. Japan's Nippon Telephone and Telegraph (NTT) laboratories are presently testing a 16-phase modulation technique. The associated high-speed circuitry required for signal phase detection

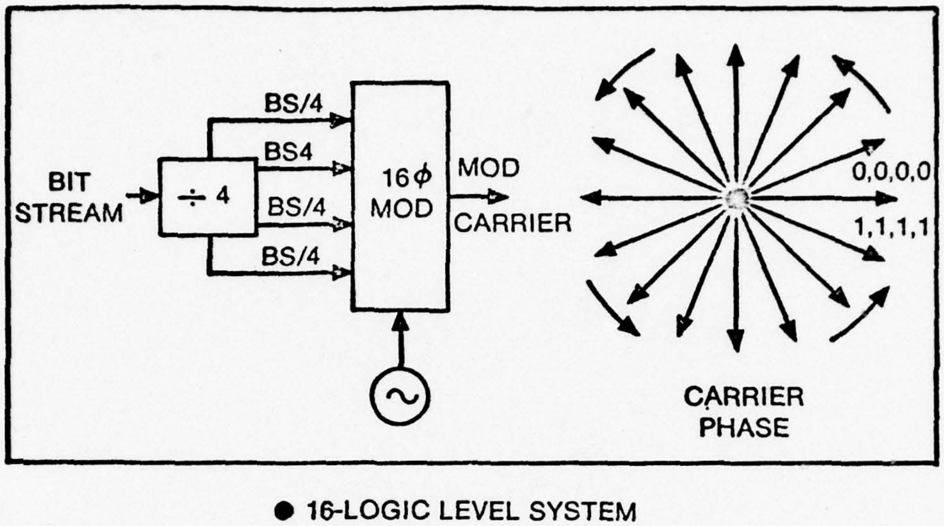


Figure 3-9. Sixteen Phase Shift Keying

(Source: "Digital Microwave Transmission Engineering Symposium." Rockwell International, Collins Commercial Telecommunications Division, p. 3-25, Figure 27.)

apparently will rely on future developments in integrated circuit technology.

A graph depicting PSK modulation techniques is presented to show the tradeoff of bandwidth versus bit error rate (BER) performance. Figure 3-10 shows the BER Curves (theoretical) for the four PSK techniques discussed.

The BER curves were derived using the following assumptions:[20]

(1) Fixed Symbol Rate

(2) Constant Bandwidth

(3) Optimum Shaping and Filtering in System Implementation

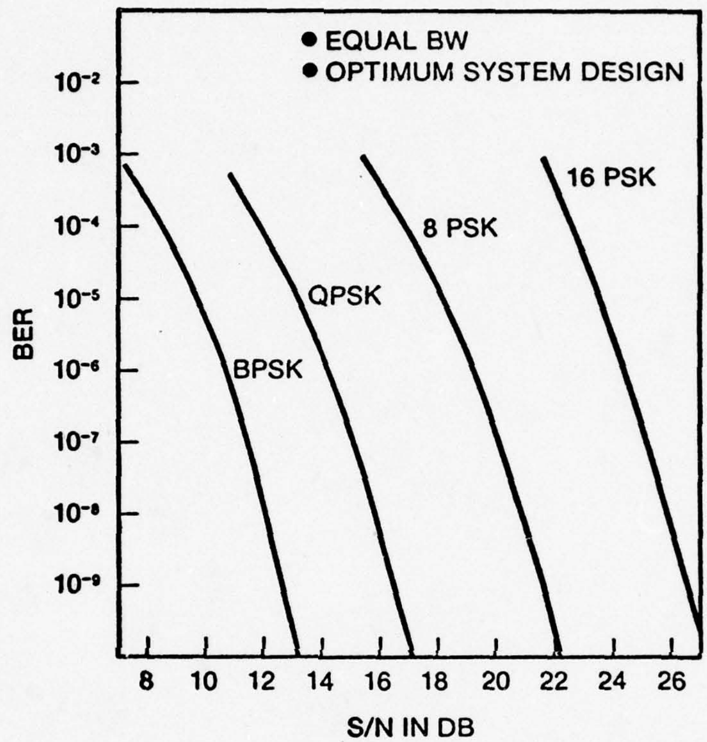


Figure 3-10. Theoretical BER Curves

(Source: "Digital Microwave Transmission Engineering Symposium." Rockwell International, Collins Commercial Telecommunications Division, p. 3-28, Figure 30.)

Quadrature Partial Response System (QPRS)

QPRS is a combination of QPSK and partial response filtering to obtain greater bandwidth efficiency. Figure 3-11 shows a block diagram of this modulation technique. The input data bit stream is divided as shown. One bit stream, divided into two, drives the four phase modulator as shown in Figure 3-11. The other bit stream is partial response filtered to drive an amplitude modulation scheme which introduces

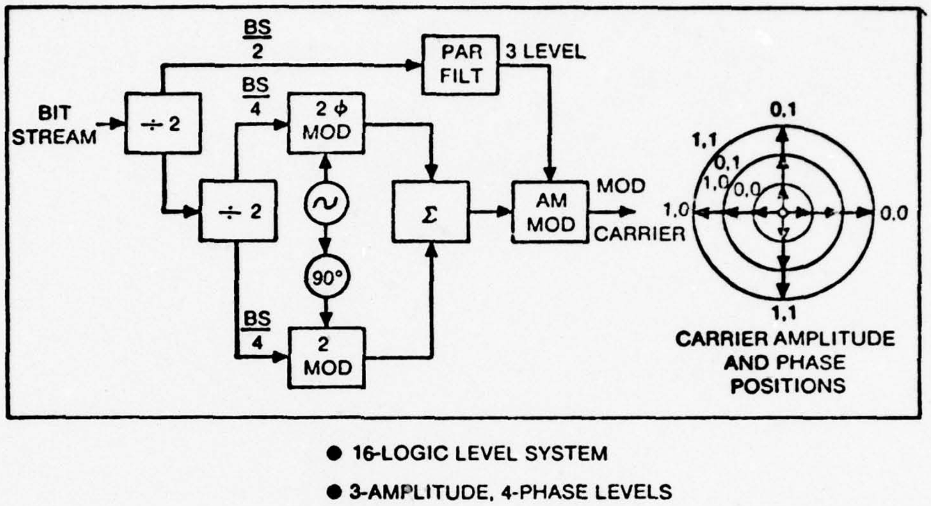


Figure 3-11. Quadrature Partial Response

(Source: "Digital Microwave Transmission Engineering Symposium." Rockwell International, Collins Commercial Telecommunications Division, p. 3-27, Figure 29.)

amplitude modulation (AM) to the RF carrier after it has been phase modulated.[21]

This 16-logic level system uses 3-amplitude and 4-phase levels for determining the phase states. The recovery process requires both envelope detection to recover the AM, and recovery of the carrier to demodulate the phase modulation. This technique also has a theoretical 4 bits per hertz spectral efficiency, and when compared with the other techniques, requires a 28.5 dB SNR for BER of 10^{-4}.[22]

Avantek and Microwave Associates both employ this technique in digital microwave radios. Practically however, this modulation technique

is capable of providing only 2 bits per hertz of occupied bandwidth with these radios , while other testing has provided a capability of 2.25 bits per hertz, as compared to the theoretical limit of 4 bits per hertz.

Prior to comparing the modulation techniques, the different detection processes are defined to provide additional information for a better understanding of Figure 3-13 and 3-14:

(1) Coherent detection which requires a locally-produced carrier with the same frequency and phase as the transmitted carrier to properly demodulate the received signal.

(2) Differentially coherent detection which does not require a reference frequency and phase signal, but only detects the change in phase between received symbol intervals. For example, in a binary system,

$+ 90^{o}$ phase change represents a 1.

$- 90^{o}$ phase change represents a 0.

(3) Non-coherent detection which does not lock the receiver in phase with the transmitter. (Used in ASK, FSK modulation.) Generally, coherent detection systems allow a lower signal to noise ratio for the same error rate when compared to a non-coherent detection system. The increase in performance of coherent detection, however, should be weighed against the consequent increase in cost and system complexity.

Comparative Analysis of Digital Modulation Techniques

The digital modulation techniques discussed earlier are listed in Table 3-1 for comparison with respect to (1) logic levels, (2) their theoretical spectrum efficiency (Bits/Hz), (3) the signal to noise ratio required within a fixed bandwidth to attain a BER of 10^{-4} with coherent detection and, (4) the relative power efficiency with respect to QPSK.

Table 3-1

COMPARISON OF DIGITAL MODULATION TECHNIQUES

Modulation Technique	Logic Levels	Spectral Efficiency *(Nyquist Bits/Hertz)	Signal to Noise Ratio with a Fixed Band-width, BER=10^{-4}, and Coherent Detection	Relative Power Efficiency to QPSK
ASK (Binary)	2	1	14.4 dB	< QPSK
FSK (Binary)	2	1	11.7 dB	< QPSK
3-Level Partial Response	3	1	21.2 dB	< QPSK
BPSK	2	1	8.4 dB	= QPSK**
QPSK	4	2	11.4 dB	—
8 PSK	8	3	16.5 dB	< QPSK
16 PSK	16	4	22.1 dB	< QPSK
QPRS	16	4	28.5 dB	< QPSK

*Practical Systems operate at a lower spectral efficiency than the theoretical limits.

**Reference: Analysis Criteria for Comparison of Techniques in this chapter.

Figures 3-12 through 3-14 provide a general performance summary for selected digital modulation techniques.

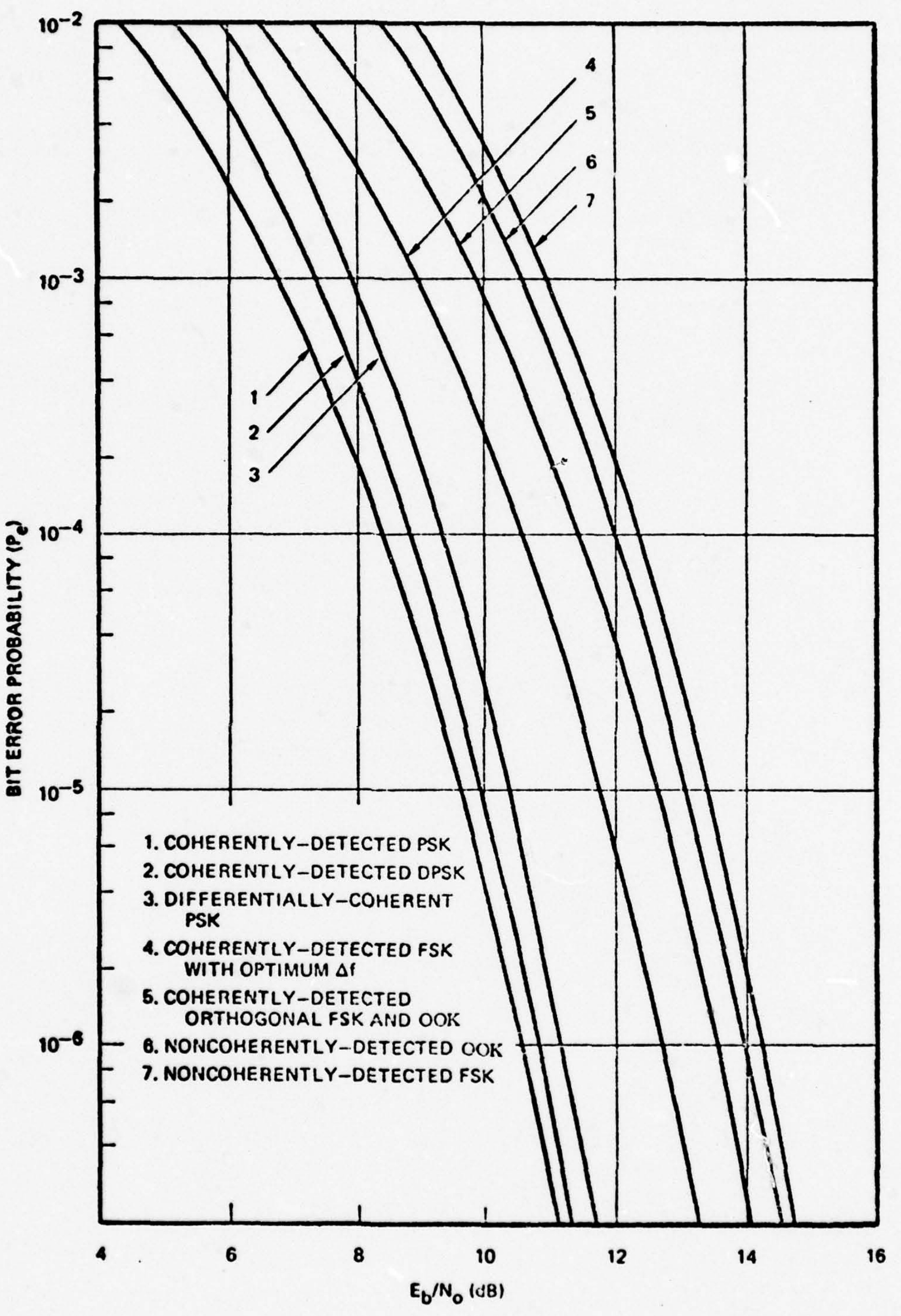


Figure 3-12. Performance Curves for Binary Modulation Techniques

(Source: AFCS Error Protection Manual, p. II-42, Figure II-20.)

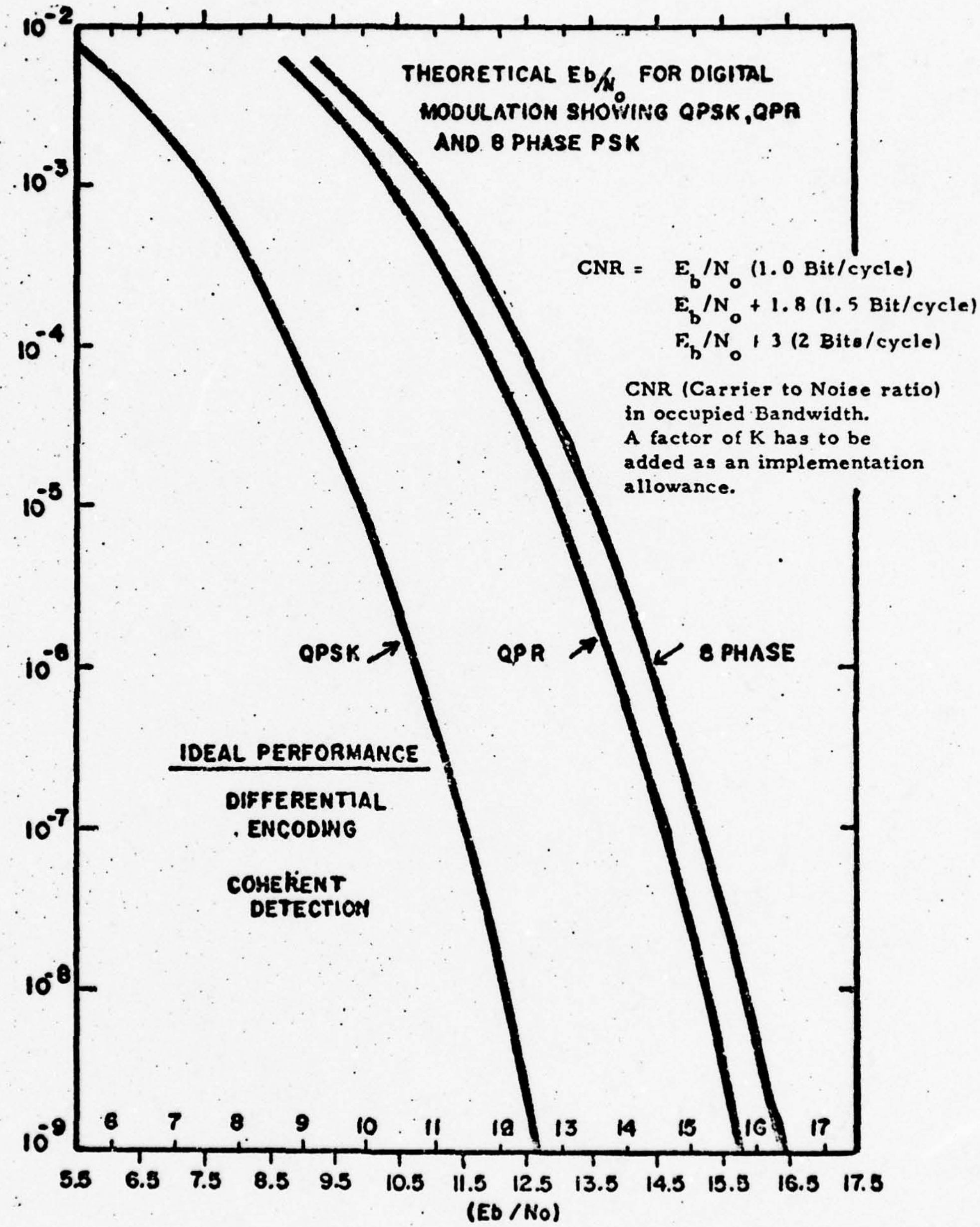


Figure 3-13. Energy per Bit as Related to Bit Error Rate (BER) for QPSK, QPRS and 8 Phase PSK

(Source: MIL STD 188-322, 15 November 1974, p. H-2, Figure H-1.)

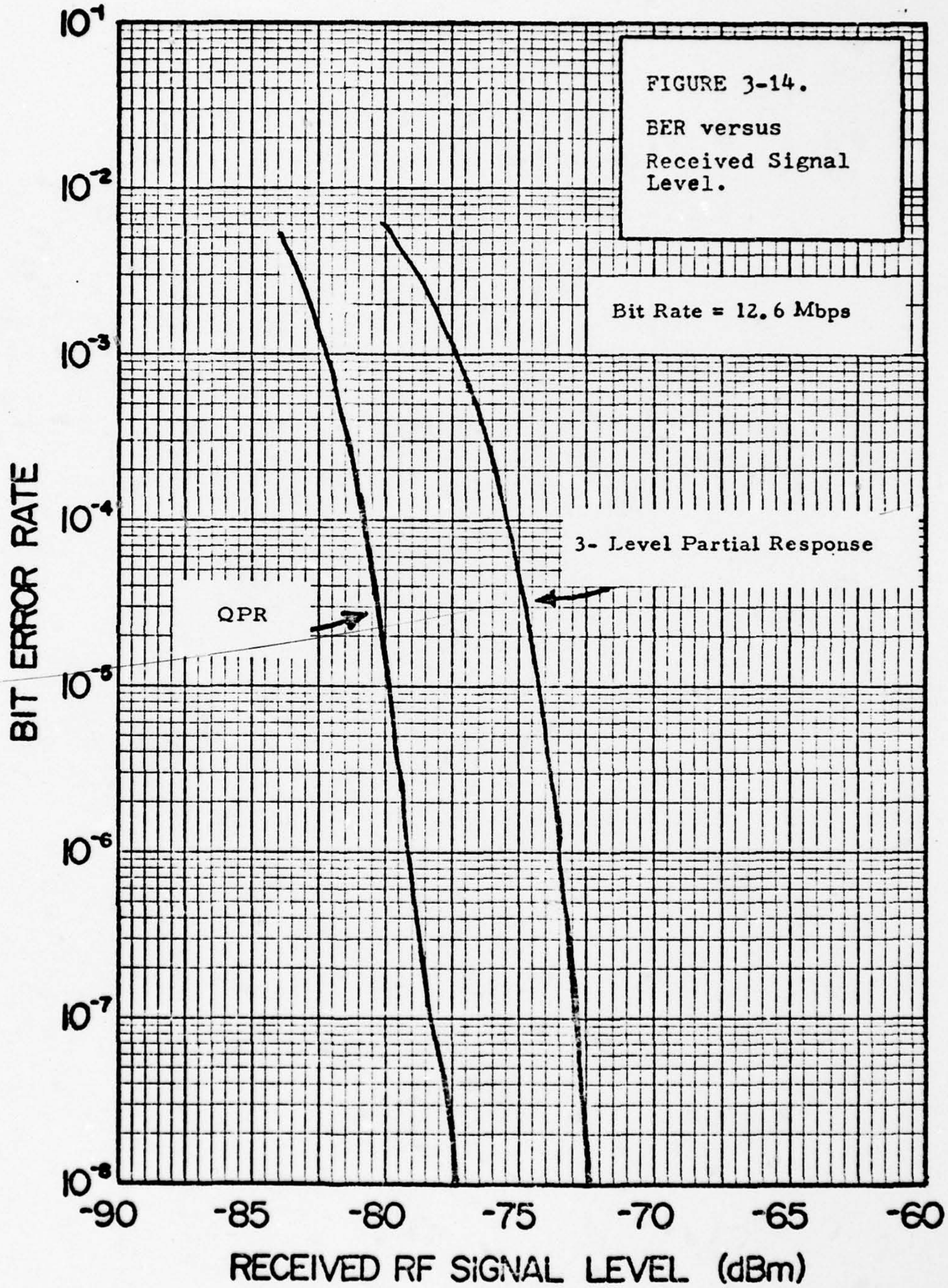


FIGURE 3-14.
BER versus
Received Signal
Level.
Bit Rate = 12.6 Mbps
3- Level Partial Response
QPR
BIT ERROR RATE
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
-90
-85
-80
-75
-70
-65
-60
RECEIVED RF SIGNAL LEVEL (dBm)

Figure 3-12 compares the ratio of energy per transmitted bit to thermal noise power density (E_b/N_o) with respect to the bit error probability. As can be seen, the more costly and complicated coherently detected PSK gives the least probability of error for a given E_b/N_o.

Figure 3-13 related E_b/N_o to the theoretical bit error rate (BER) for the QPSK, QPR, and 8-phase PSK modulation techniques under ideal performance using differential encoding and coherent detection. It is shown that quadraphase shift keying (QPSK) requires the least E_b/N_o to achieve a given BER. The relationship between the received signal level and BER for 3-level partial response and QPR modulation is depicted in Figure 3-14.

Performance of the various digital modulation techniques has been shown with respect to BER, received signal level (RSL), energy per transmitted bit to thermal noise ratio (E_b/N_o), bit error probability (P_e), detection processes, logic levels, theoretical spectral efficiency (bits/Hz), signal to noise (S/N), and power efficiency relative to QPSK.

Technologies and the Spectrum

Generally, some form of microwave transmission provides a useful service in the best interest of the nation, and necessarily occupies a portion of the frequency spectrum. Since the radio frequency spectrum is a limited natural resource, a high level of efficiency in its use must be maintained to prevent extravagant use of the spectrum. This

may not be true for waveguide system application, where channel isolation, in effect, provides an unlimited spectrum.

Early digital modulation techniques were not competitive with existing analog modulation techniques for transmission of voice frequency signals with respect to spectral efficiency. As a result, during the late sixties and early seventies, digital microwave transmission technology had complicated the classic spectrum problem of bandwidth utilization, by introducing a technology which was less bandwidth efficient than the current analog modulation technology. This, together with potential interference problems between analog and digital systems, accounted for the numerous divergent technical and managerial opinions concerning the use of the frequency spectrum. A more fundamental question based on these problems is whether or not digital microwave transmission should even be allowed, or if allowed, in what part of the frequency spectrum?

Interference of digital with analog systems is of primary importance in the frequency bands below 15 GHz as this is the part of the frequency spectrum, where most all of the current analog, broadband communication systems are operating.

Vast quantities of FDM-FM analog plant and equipment are in use throughout the world, providing communications for millions of people.

The technical aspects of the problems of interference and spectral efficiency are further discussed here to provide the requisite background for portions of Chapter Four. In order for widespread digital microwave

transmission to be possible, regulatory policies regarding interference had to be developed. One aspect of the regulation was the "mask" limits specified by the FCC regarding energy emission. (Reference Figure 3-15, FCC Emission Limitations.) The following formula can be used to define the power in any 4 KHz band, stipulating that no energy shall be outside the authorized bandwidth in excess of 50 dB below the desired signal:

$$P = P_o - 35 - 80\ ((f - f_o)/B - 10 \log B)$$

P = power in any 4 KHz band in dBm

P_o = mean power output in dBm

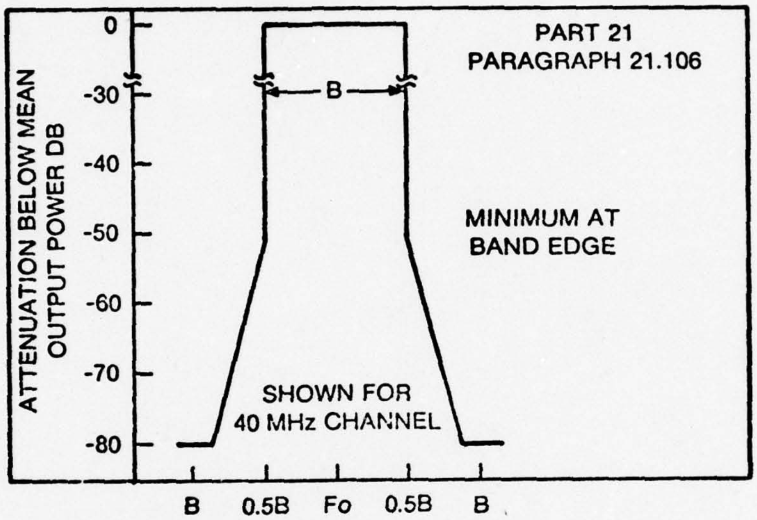
f = center frequency of 4 KHz band in MHz

f_o = center frequency of authorized band in MHz

B = authorized bandwidth in MHz

Figure 3-16 shows the typical RF energy spectrums of an analog FDM-FM system, a digital QPSK system, and a Three-Level Partial Response system with the digital "mask" limits established by the FCC.

The occupied bandwidths for the various modulation techniques are based on (1) equal unmodulated power (0 on dB scale), (2) equal radio channel bandwidth, and (3) a 10 KHz IF bandwidth on the spectrum analyzer. Examination of the graphs in Figure 3-16 shows an approximate difference of 20 dB in peak signal strength between the two modulation techniques. The digital radio converts most of its signal power into useful sideband information, whereas, the FM system has a strong carrier component, 50 dB above the information bearing sidebands.



BAND EDGE EMISSIONS ARE:

- AT LEAST 50 DB
- A = 35 +0.8 (P-50) +10 LOG B

  A - MEAN POWER OUTPUT

  P - PERCENT REMOVED FROM CARRIER FREQUENCY Fo

  B - AUTHORIZED BANDWIDTH (MHZ)

Figure 3-15. FCC Emission Limitations

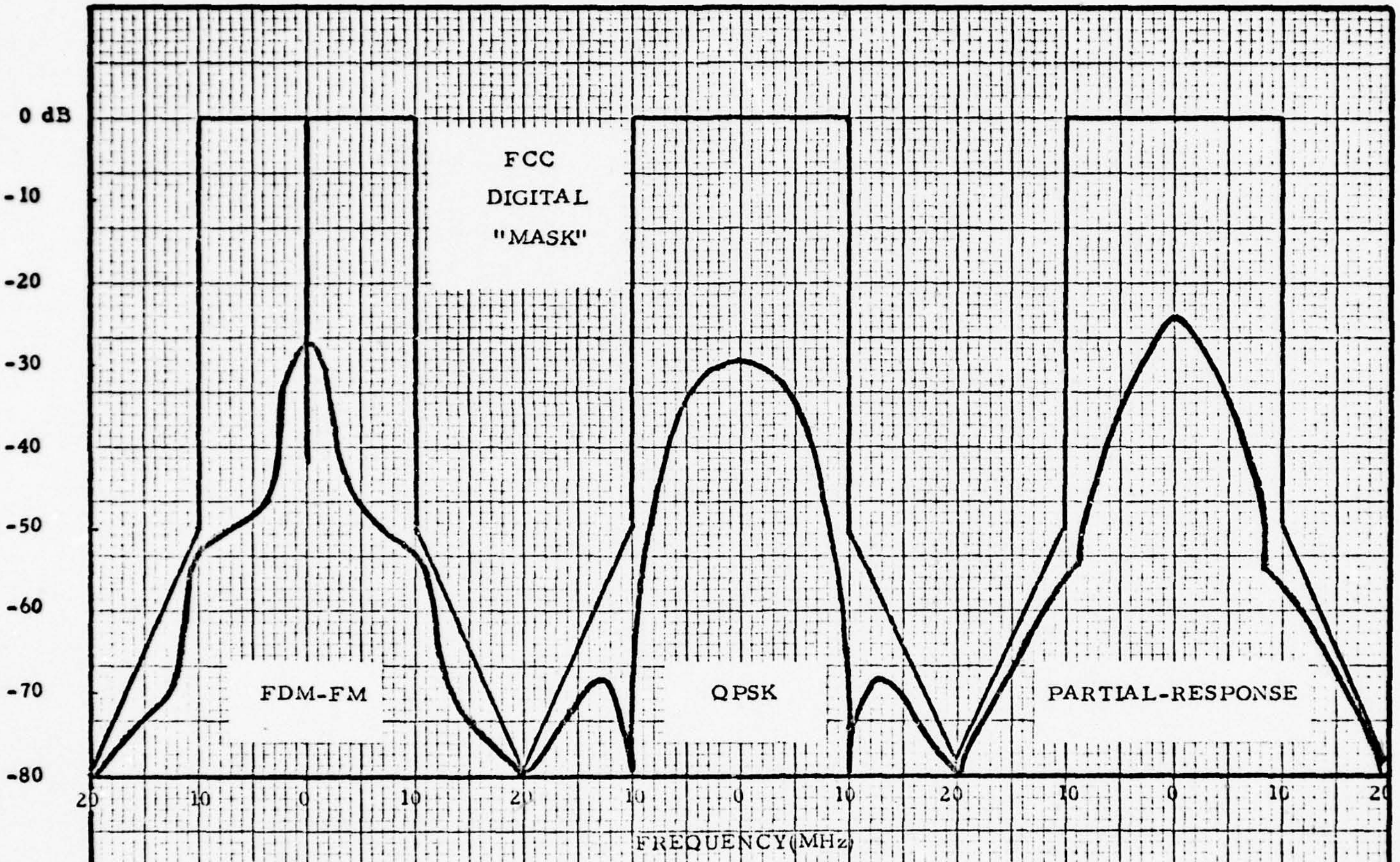


Figure 3-16. System Energy Spectrum within FCC Digital "Mask"

The strong carrier can be a source of interference to other FDM-FM systems. As a result of this potential interference between adjacent FDM-FM radio systems, a minimum frequency spacing of 30 MHz, plus polarization isolation, is used on high-density telephone routes. In contrast, the QPSK digital radio can be placed with the main lobe as shown in Figure 3-16, immediately adjacent to the main lobe of the next RF digital channel.[23]

Digital microwave radios can operate successfully with high-level interference and themselves offer little interference to other digital systems, but can be destructive to analog FDM-FM systems. The high interference tolerance of digital modulation techniques permit system designers to employ strategies which partially compensate for the extravagant use of RF bandwidth requirements. The same is not true of analog systems; and therefore a distinction must be made between an all-digital environment (high interference tolerance), and an analog/digital system (reduced interference tolerance).

The problems of efficiency and spectrum utilization are interrelated and are discussed together. Greater utilization of the frequency spectrum can be realized if the modulation technique has a format similar to that of the information to be sent, i.e., digital modulation for discrete state information (data), and analog modulation for continuous information such as speech.[24]

In practical digital systems, the requirement to band-limit the transmitted spectrum to fit available bandwidth is essential. Equally

important is the need to control emitted power spillover into adjacent channels. Wideband filtering is desirable for achieving accurate reproduction of the transmitted spectrum, however this does not efficiently utilize the spectrum. To achieve bandwidth efficiency, narrow bandwidth is required, resulting in a tradeoff of occupied bandwidth versus system or BER performance.

Choosing among the various modulation techniques depends on many factors such as performance under expected transmission medium characteristics, economics, system capacity, available technology, and existing frequency spectrum allocations. The use of digital microwave systems in the lower frequency bands where interference-sensitive FDM-FM systems operate will require optimum care to conserve RF spectrum, and to prevent or minimize the interference to adjacent FDM-FM analog systems.

The problem of how to define spectrum efficiency has become a quasi-political/technical problem and is as yet still not clearly defined. Industry's response to Docket No. 19311 reflected this issue in that certain sectors of industry had developed digital techniques with a desire to introduce them into the communications market. The specifications describing their equipment were biased by their beliefs which made them appear more spectrum efficient than they actually were by other criteria. On the other hand, those corporations with a large investment in existing plant and research and development in analog systems favored action on

the part of the FCC to prohibit, or delay the introduction of digital transmission technology. Restriction on occupied bandwidth, and emitted power limitation should be standardized to provide a common reference for a valid analysis of modulation techniques.[25] In Chapter Four, Political and Quasi Technical Problems, the rationale behind the different viewpoints expressed is developed with regard to digital transmission technologies.

Included in Chapter Four is a discussion of the regulatory implications of digital system interference with existing analog systems, and the professed extravagant use of RF spectrum as analyzed through the FCC Docket No. 19311.

CHAPTER 3

Footnotes

1. John F. Beckerich and Kerry R. Fox. "The Maturing of Digital Microwave Radio." Signal. April 1976, p. 4.

2. "Digital Microwave Transmission Engineering Symposium." Rockwell International, Collins Commercial Telecommunications Division. April 18-21, 1977, Dallas, Texas. p. 3-17.

3. Ibid., p. 3-28.

4. L. Bruce Johnson. "Improve Microwave Performance with Digital Modulation." Telephony. May 8, 1972, p. 3.

5. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 3-28.

6. Johnson, op. cit., p. 3.

7. Joseph F. Balcewicz, Martin Hecht, and H. Robert Mathwich. "The Effect of Tandem Band and Amplitude Limiting on the E_b/N_o Performance of Minimum (Frequency) Shift Keying (MSK). IEEE Transactions on Communications. October, 1974, p. 1526.

8. VICOM. PSB-6004, Digital Multiplexer Description, Operation and Theory of Operation. April, 1972, p. 3-4.

9. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 3-28.

10. A.C. Walker. "PCM Multiplexers for Microwave." VICOM.

11. R. Rearwin and A.C. Walker. "Digital Modulation Techniques." Microwave Associates, and VICOM.

12. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 3-28.

13. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 4-11.

14. A.C. Walker and William H. Smith. "PCM Microwave Links." Telecommunications. April, 1973, p. 28.

15. International Radio Consultative Committee. "Radio Relay Systems for the Transmission of Pulse-Code Modulation and Other Types of Digital Signals. Report 378-1." XIIth Plenary Assembly, New Delhi, 1970. Vol. IV, Part 1, pp. 178-183.

16. James S. Gray. "Quadraphase PSK Modulation Technique Permits Data Transmission at 1 Gbps." Communications Design. December, 1972, p. 3.

17. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 4-12.

18. Ibid., p. 5-6.

19. J.F. Beckerich and J.H. Ingram. "IS 'Cross-Pol' the Way to Go for 11 GHz Digital LOS Radio." Telephone Engineer and Management. November, 1976, p. 5.

20. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 4-10, 11.

21. "MDR-11/DMX-13 Microwave Digital Radio System." Collins Radio Group, Rockwell International. Dallas, Texas. Product Description, 1977, p. 32.

22. "Digital Microwave Transmission Engineering Symposium." op. cit., p. 3-28.

23. Johnson, op. cit., p. 1.

24. William R. Bennett, and James R. Davey. Data Transmission. San Francisco, McGraw-Hill Book Company, 1965, p. 225-239.

25. Federal Communications Commission. Notice of Proposed Rule Making. Adopted: May 3, 1973, Released: May 8, 1973. p. 71:150-71:155.

CHAPTER 4

THE MILITARY AND SPECTRUM ALLOCATION

The proposed application of the digital modulation techniques in the established microwave radio bands was the cause for concern in two areas:[1]

1. The extravagant use of the RF spectrum, in terms of emission bandwidth, for voice transmission compared to conventional FDM-FM systems.
2. The potential interference of the proposed digital systems with existing and planned FDM-FM radio systems.

These concerns were based largely on the limited experience with 2-level FSK and PSK techniques whose practical spectral efficiencies approximated 0.5 bits per second per Hertz (b/s/Hz) and the 3-level partial response FM and QPSK whose efficiencies approximated 1 b/s/Hz.[2]

This chapter focuses on the regulatory, political and technical problems associated with the two concerns cited above and how they impacted the ability of the Military to satisfy successfully and economically the digital requirements set up by the Secretary of Defense.[3]

Spectrum Considerations and Their Impact

Magnitude of the Military's Spectrum Resource

As a result of previous regulatory action, i.e., the Communications Act of 1934, on the national level, and the Radio Regulations annexed to the International Telecommunications Convention signed in Geneva, Switzerland on December 21, 1959,[4] at the international level, the radio frequency spectrum has been divided and subdivided into bands to be utilized by specific radio services (i.e., Fixed Station Microwave, Fixed Satellite, Navigational, Broadcasting). This action was necessary so that users of the spectrum could secure reliable interference-free communications. Of particular importance to the Military was digital transmission in the four, seven, and eight GHz microwave radio bands.[5] All present military microwave radio equipment within the Defense Communications System (DCS) operate within these bands. Because of economics and equipment commonality considerations, the Military was concerned about using the same frequency bands for digital transmission, as was currently being used for existing FDM-FM systems. It was also felt that requesting new microwave bands from the U.S. Government or from foreign countries would likely meet with little success.

Competition for the Radio Spectrum

Nationally, the military services (Air Force, Navy, and Army) rank two, three, and four in the use of the radio spectrum. The number

one government user is the Department of Transportation. At the end of the January 1974 reporting period, the MILDEPS had accounted for 44.62 percent of the allocation. As an entity, the U.S. Military departments (MILDEPS) accounted for 41.21 percent of the total government allocated spectrum during the period 1 January to 30 June 1976.[6] In two and one-half years, the MILDEPS lost 3.41 percent of their allocations while the Department of Transportation gained 2.56 percent of the government allocations.[7] This indicates that the MILDEPS are losing ground to other government users. Furthermore, the increase in the number of specialized common carriers has increased the pressure on the government to give up or to share more of the government microwave and satellite frequency bands. Internationally, the U.S. Military faces competition from like services of other nations.

As mentioned earlier, the radio spectrum has been divided into service bands. These divisions have, in principle, been agreed to by most all of the 148 member nations of the International Telecommunications Untion (ITU). Even though this has been accomplished, there is no rule, written or unwritten, that permits the U.S. Military to use frequencies in another country without the expressed permission of that country. To compensate for this, the U.S. Military depends on Defense Treaties and Status of Forces Agreements to obtain recognition for their frequency requirements. At best this is not an easy task.

It is not unlikely for the nationally designated military microwave bands to be utilized by the host country Post Telephone and Telegraph (PTT)

Ministry for its own civil and military long haul communications. This being the case, the U.S. Military, in accordance with the beforementioned treaties and agreements, would have to negotiate with the host country frequency coordinator to share the bands.

One such example occurred in the late sixties and involved the two and eight GHz bands in the Federal Republic of Germany (FRG). The U.S. Military had agreed to evacuate the two GHz band and use the eight GHz band to support the U.S. Military requirements. It became apparent however, that not all the communications requirements could be met within the remaining military bands. The FRG consequently agreed to share a part of the eight GHz band, which was previously allocated exclusively to Civilian fixed communications services, with the U.S. Military.

A key factor in obtaining the required frequency and bandwidth assignments from the host country is demonstrating that use of the requested assignments will have no destructive impact on the existing electromagnetic environment. This is accomplished by detailed electromagnetic compatibility (EMC) analyses that require extensive modeling of potential interference, based on knowledge of the equipment characteristics and of the local EMC environment.

The Department of Defense (DoD) established the Electromagnetic Compatibility Analysis Center (ECAC), by DoD memorandum in June 1960, in recognition that action was required to cope with the increasing number and severity of EMC problems.[8]

A bilateral agreement between the DoD (ECAC) and the Federal Republic of Germany's Bundespost Ministerim Oberamstrat (frequency office) was consumated in 1967 and provided for the exchange of EMC modeling, analysis techniques, and data bases.

These services were utilized extensively for the European Wideband Communications System (EWCS) and the FKV.

The Military and Spectrum Management

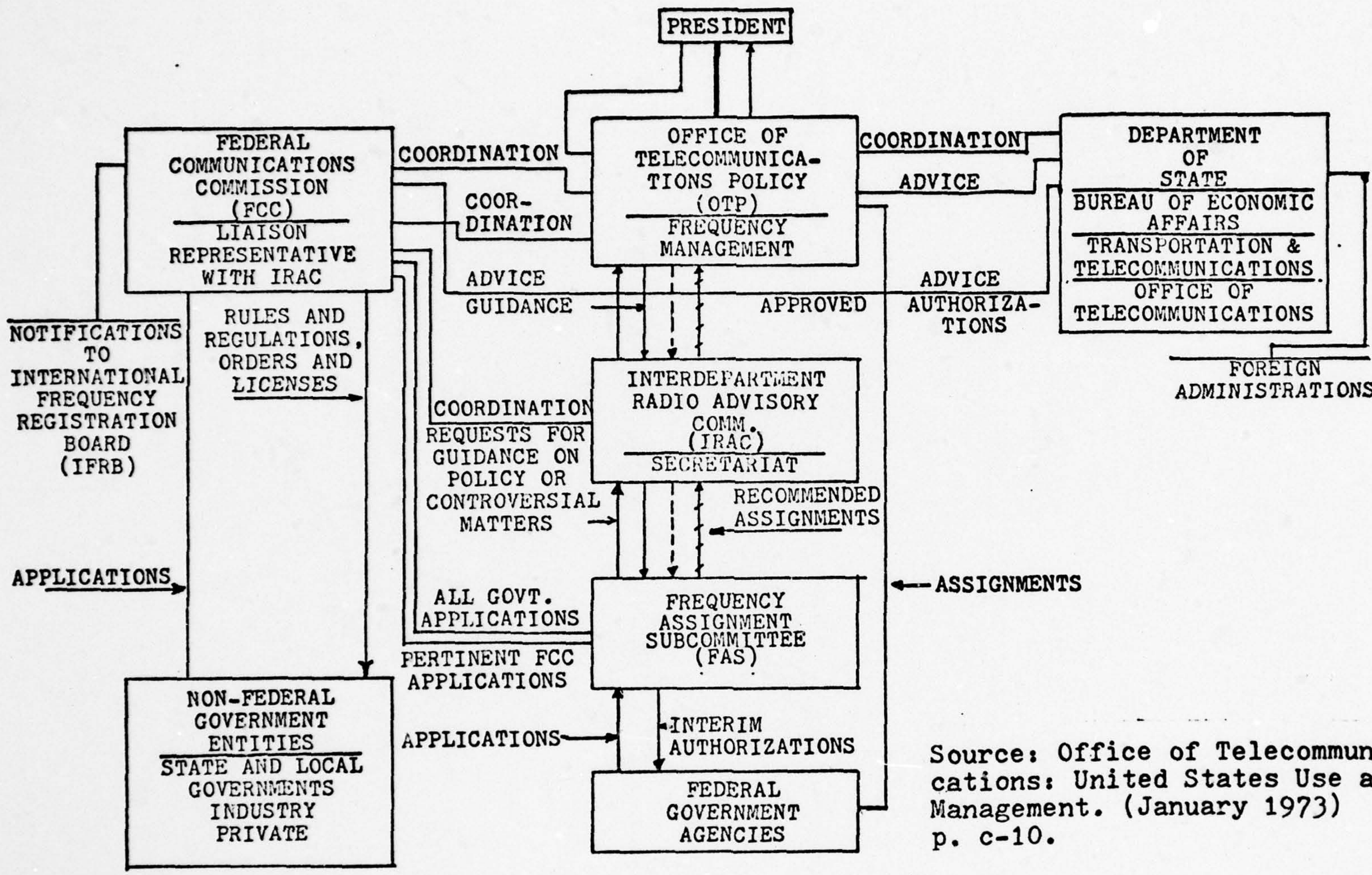
Traditionally, spectrum management has been primarily a matter of record keeping, i.e., logging out frequencies to applicants on a first come, first served basis. The primary concern was to accommodate each demand within the bounds of prestructured regulations. This approach was satisfactory for a sparsely populated electromagnetic environment, but now it leads to inefficiencies in spectrum usage. This is becoming more intolerable in the face of continuously growing demands on the limited spectrum resource. Spectrum management has gradually moved toward a new philosophy of allocations that is causing spectrum engineering to move away from the rigidly structured frequency and bandwidth assignment rules, toward assignments based on optimum spectrum sharing subject to technical assessment of the applicant's needs and relevant EMC analysis.[9]

Until recently, advances in technology and limited demands for spectrum allocation have prevented serious congestion and interference. Now, however, the situation is reversed and demands for spectrum

space are coming faster than methods to conserve this resource are being developed. Therefore, careful management and regulation, nationally and internationally, of this scarce natural resource is mandatory. This problem was addressed by the General Accounting Office in 1974.[10]

Regulation of the U.S. Government's use of the radio frequency spectrum is the primary mission of the Office of Telecommunications Policy (OTP). The principal function of regulation was specifically assigned to the President by the Communications Act of 1934. The Presidential duties in this regard were assigned to the Director of Telecommunications by the 1970 Reorganization Plan No. 1 and Executive Order 11556.[11]

Nationally, regulation of the non-government sector is accomplished by the Federal Communications Commission (FCC) and as noted above, the government sector is regulated by the OTP. This twin management of the radio spectrum is accomplished on a day to day basis through close contact by the OTP with the FCC and other Federal agency staffs. The more formal management of the government spectrum allocations is conducted through the Interdepartment Radio Advisory Committee (IRAC) and its associated subcommittees, those being the Spectrum Planning Subcommittee (SPS), the Frequency Assignment Subcommittee (FAS), the Technical Subcommittee (TSC) and the International Notification Group (ING). A graphic illustration of this management system is depicted in Figure 4-1 titled National Frequency Coordination and Assignment.[12]



Source: Office of Telecommunications: United States Use and Management. (January 1973) p. c-10.

Figure 4-1. National Frequency Coordination and Assignment

The IRAC[13] currently consists of 18 member Federal departments and agencies together with such other departments and agencies as the Assistant Director for Frequency Management might designate.

The Frequency Assignment Subcommittee (FAS) is responsible for the development and execution of procedures for the assignment and coordination of the radio frequencies used by the Federal Government. Interim action of the FAS is taken by the Aeronautical Assignment Group (AAG) in connection with certain frequency assignment actions in designated bands of primary concern to the aeronautical radio navigation services. The Military Assignment Group (MAG) of the FAS takes interim action, on behalf of the FAS, in connection with certain frequency assignment actions in designated radio frequency bands of primary concern to the Military. The MAG is chaired by a representative of the U.S. Air Force.

The Spectrum Planning Subcommittee (SPS) carries out the function of the IRAC that pertains to the planning for the use of the electromagnetic spectrum in the National interest. This includes the apportionment of spectrum space to support established or anticipated radio services, as well as the apportionment of radio spectrum to be shared between Government and non-Government activities. The SPS is also responsible for the preparatory work relating to frequency matters to be brought before international conferences. Development of Electromagnetic Compatibility (EMC) procedures is also a major responsibility of the SPS.

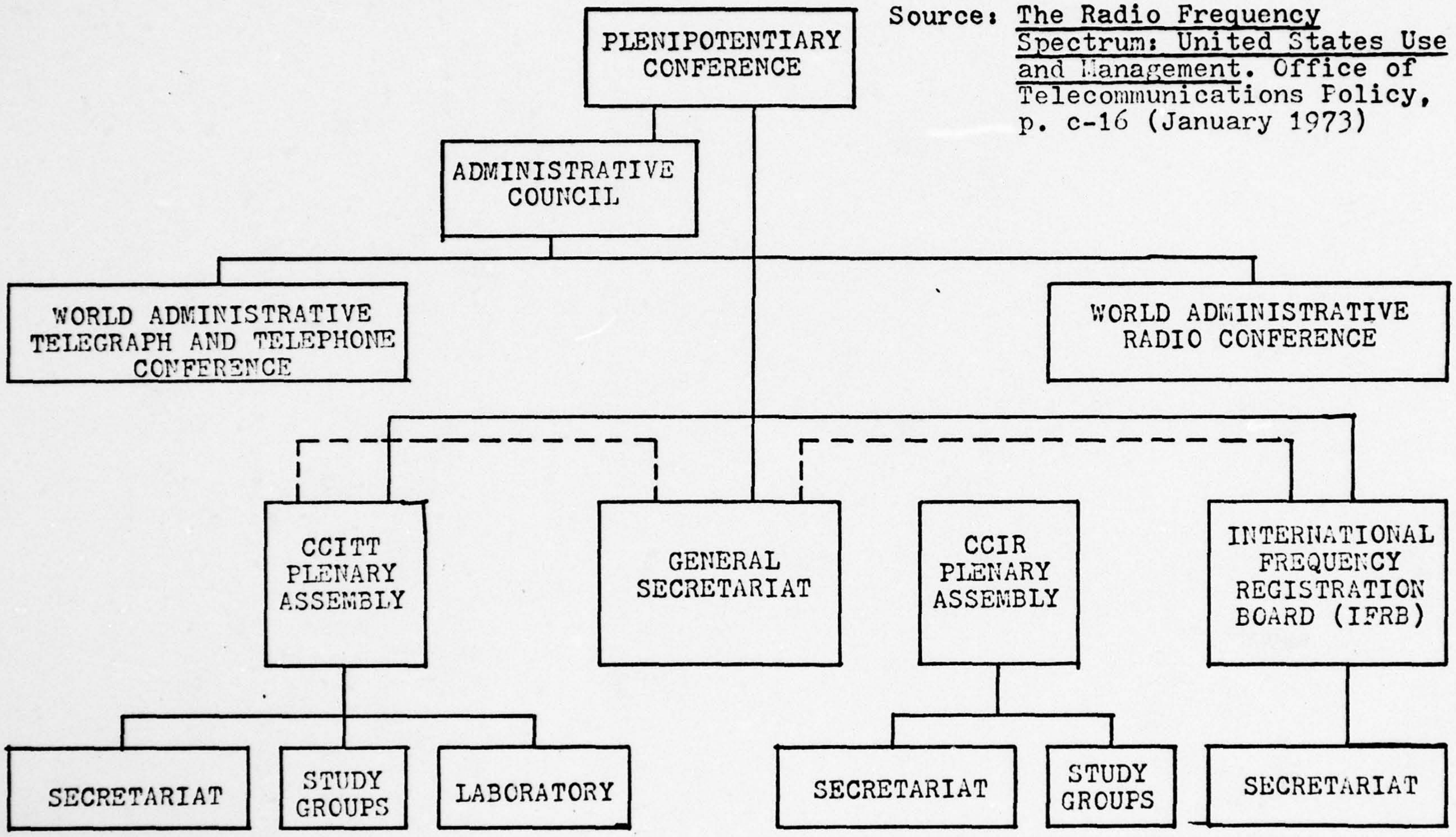
The development of standards, new or improved, pertaining to uses of the radio frequency spectrum and to electromagnetic compatibility (EMC), is the responsibility of the Technical Subcommittee (TSC).

Responses to the International Telecommunications Union concerning questionnaires and other correspondence relating to the notification of frequency assignments used by the United States is the responsibility of the International Notification Group (ING).

Internationally, regulation of the radio spectrum is accomplished through the activities of the International Telecommunications Union (ITU) which is currently composed of 148 member nations, with a one nation, one vote policy. The organization[14] of the ITU and its committees, secretariats and study groups is shown in Figure 4-2.

The International Telecommunications Union is an international body whose chief purpose is to maintain and extend international cooperation for the improvement and rational use of telecommunications. It was formed in 1932 in Madrid, Spain and replaced the International Telegraph Union which was established at Paris, France in 1865.

It is through the efforts of this international organization that experimental or technological data and engineering considerations are made available for the formulation of international regulations. Significant contributions for the formulation of the international regulations are made by interested industrial, scientific, academic and professional organizations. These organizations[15] participate on the Consultative



Source: <u>The Radio Frequency Spectrum: United States Use and Management</u>. Office of Telecommunications Policy, p. c-16 (January 1973)

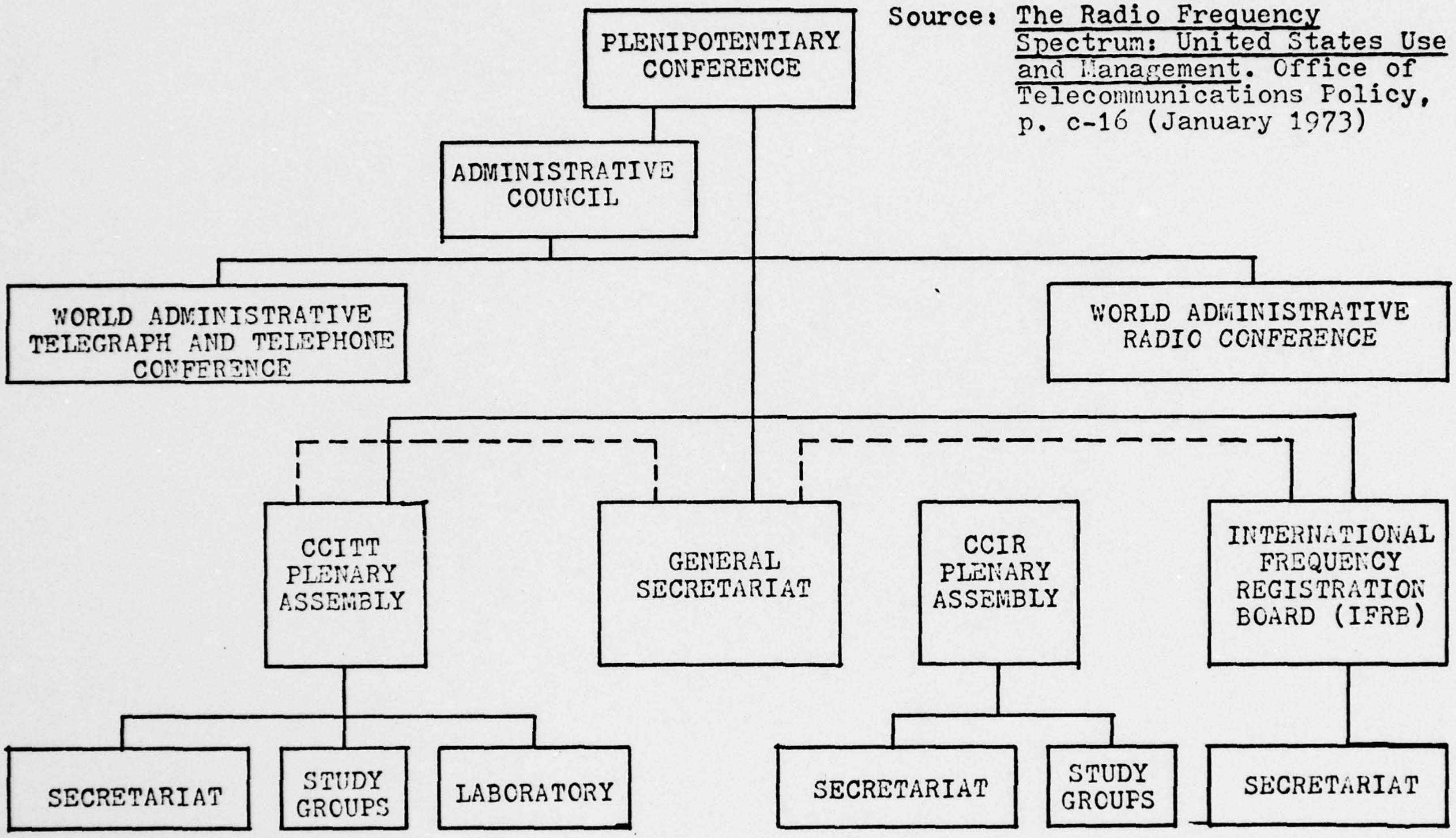
Figure 4-2. International Telecommunication Union Organization

Committees of the ITU. There are two such committees at the present time. They are the International Telephone and Telegraph Consultative Committee (CCITT) and the International Radio Consultative Committee (CCIR). The CCITT deals with wire, cable, and piped communications. The CCIR deals with telecommunications over the radio (radiating) modes of propagation.

For the purposes of this project, the CCIR is of the most importance. Work within the CCIR is carried out through the activities of thirteen Study Groups (SG) which are listed in Table 4-1.

Each study group normally holds two international meetings between the plenipotentiary meetings which occur every seven to eight years. The works of each group are presented to the Plenary Assembly. Approximately one year after the Plenary Assembly, the documents that have been approved are issued in three languages (French, English, and Spanish). The English version of the texts are green covered volumes and are referred to as "the green books."

The material contained in the Green Books[16] appear as a QUESTION, which identifies a technical or operational problem, a STUDY PROGRAM, which describes how the work on a problem (such as defined by a QUESTION) is to be carried out, or a DECISION, which is an instruction on the organization of the work of a Study Group such as establishing an Interim Working Party (IWP).



Source: The Radio Frequency Spectrum: United States Use and Management. Office of Telecommunications Policy, p. c-16 (January 1973)

Figure 4-2. International Telecommunication Union Organization

Table 4-1

CCIR STUDY GROUPS

S.G. 1	Spectrum Utilization and Monitoring, Vol. I
S.G. 2	Space Research and Radioastronomy, Vol. II
S.G. 3	Fixed Service at Frequencies Below About 30 MHz, Vol. III
S.G. 4	Fixed Service Using Communicatic Satellites, Vol. IV
S.G. 5	Propagation in Nonionized Media, Vol. V
S.G. 6	Ionospheric Propagation, Vol. VI
S.G. 7	Standard Frequency and Time-Signal Services, Vol. VII
S.G. 8	Mobile Services, Vol. VIII
S.G. 9	Fixed Service Using Radio-relay Systems, Vol. IX
S.G.10	Broadcasting Service (Sound) Including Audio Recording and Satellite Applications, Vol. X
S.G.11	Broadcasting Service (Television) Including Video Recording and Satellite Applications, Vol. XI
CMTT	Transmission of Sound Broadcasting and Television Signals over Long Distances (Joint with CCITT), Vol. XII
CMV	Vocabulary (Joint with CCITT), Vol. XIII

Further, the Study Group's provisional answer to a QUESTION or STUDY PROGRAM is incorporated into a REPORT. Once the Study Group considers its answers adequate to serve as a foundation for international cooperation (i.e. as in the Radio Regulations), the REPORT is reformulated, in whole or in part, and becomes a RECOMMENDATION. Finally, the Study Groups may direct a proposal or a request, as an OPINION, to other international organizations.

As such, the Green Book Volumes contain the recommended standards for the international engineering, scientific, and industrial communities as well as the international market place. They can be considered as handbooks within their respective areas of study.

Regulatory Problems

Given the requirement by the Office of the Secretary of Defense (OSD) to provide digital communication and the motivations for the use of the digital techniques, the Military was looking for some way to satisfy the requirement economically. A better picture of the military situation with regard to available digital communication system hardware can be seen by looking at what was happening at the national level in the early 1970's.

FCC Notice of Inquiry Docket No. 19311

During the late 60's and early 70's the Federal Communications Commission was asked to rule on requests by the upcoming specialized common carriers for the use of digital transmission techniques.

Almost a year after the requests came to the attention of the FCC, the Commission released a Notice of Inquiry (September 15, 1971) to industry asking thirteen related questions concerning the digital mode of microwave transmission. The inquiry cited the claimed advantages of various digital techniques and further cited two areas of major concern, "inefficient spectrum utilization and a greater potential for harmful interference with existing services."[17]

It was further stated that "Only two digital systems via microwave radio (both common carrier) are known to be utilized at present."[18] The two systems provided emergency relief of overloaded trunks between Staten Island and Brooklyn (New York Telephone Company) and provided facilities between Cincinnati, Ohio and Atlanta, Georgia (Western Union Telegraph Company).

Dates for filing direct and reply comments were set for November 15, and December 16, 1971, respectively. The Data Transmission Company (DATRAN) requested that the time for filing reply comments be extended until January 17, 1972[19] because they had not been able to obtain copies of comments of some twenty respondents in time to adequately review their comments. The extension was granted on December 13, 1971.

Responses by Industry

The responses by industry fell into three basic categories: first, areas of broad technical concensus; second, areas of vigorous disagreement; and third, areas of obvious "self-interest," i.e., some organizations issued responses void of the spirit of the Docket Inquiry and recognition of the problem.[20,21,22]

In the area of broad technical concensus, most companies agreed that digital modulation techniques should be permitted with analog techniques at frequencies below 15 GHz, and in the bands above 15 GHz, they should be the rule. Also, all were in agreement that digital communication requirements would be rising sharply.

There was disagreement as to how much interference there would be between the digital and analog systems. With respect to allowing digital transmission in the two and eleven GHz bands, two companies (MCI and GTE) were opposed. They claimed there wasn't enough known about the potential interference problems, and that the problem of interference should be studied further.

The degree of digital spectral efficiency as opposed to analog spectral efficiency was not agreed upon, and technical limitations with respect to how much RF filtering would be required to limit the radiated spectrum also caused differences in the answers and view points of the respondents.

FCC Action During the Inquiry

As can be seen from the dates on the initial Notice of Inquiry released on September 15, 1971, and the Notice of Proposed Rule Making on May 8, 1973, the FCC was twenty months making a decision that would still require another twnety-two months to finalize. Final actions and guidance were completed in September, 1975.

Even as the FCC was caught up in making a determination on the use of the digital microwave transmission technology, DATRAN was given FCC approval to use the digital technology over bitter opposition by AT&T, in June, 1971.[23]

AT&T, in October 1972, applied to the FCC to use the digital technology for their "data-under-voice" (DUV) network.[24] The AT&T application was approved in June, 1973, but the issue of what rates the company should charge for the service was left unresolved.[25]

A Notice of Proposed Rule Making, released by the FCC on May 8, 1973, contained the results of the inquiry and established the guidelines for the use of the digital modulation techniques in microwave radio. The notice[26] also proposed ammendments to Part 2 (Bandwidth calculations) and Part 21 (Emission Limitations) of Title 47 of the Code of Federal Regulations.

Basically, the Commission authorized the use of the digital modulation techniques in all the microwave bands, but stipulated the use of RF filters below 15 GHz to reduce interference with adjacent FDM-FM microwave links. They also proposed modifications to

existing Code of Federal Regulations tables for the calculation of necessary bandwidth. The Commission elected not to confine the use of the spectrum above 15 GHz to the digital modulation techniques, as recommended by some respondents.

Impact on Industry and Military Hardware

Because of the lag in regulatory action, equipment manufacturers were reluctant to start producing hardware that might not be acceptable to the FCC. The Military, as a result, could not find commercial equipment that could be adapted to meet their requirements for a digital microwave transmission system and consequently had to initiate actions to provide an interim solution.

Political and Quasi Technical Problems

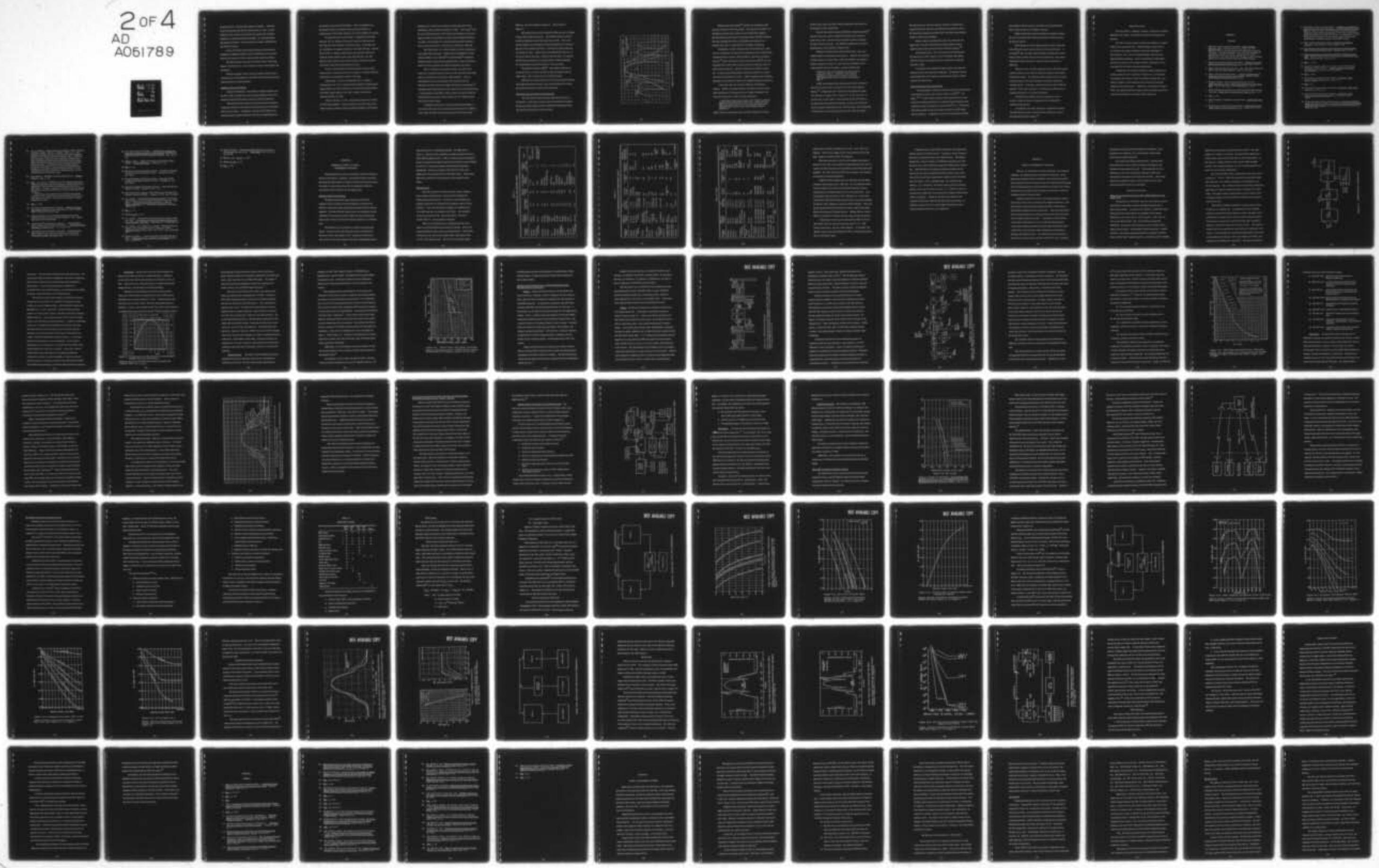
The time is gone, if it ever really existed, when problems of a technical nature can remain purely technical. Today, almost every technical problem reaches, sometimes unobtrusively, into the bowels of the political and economic environments.

The work of project engineers and their strong beliefs in technologies, bias their arguments, their protests, and their formulation of marketable products. In essence, this work and belief has become their life and often dominates the character of the company for which they work. Rightly so, for it is in the beliefs that they have worked so hard and so long to develop and promulgate, that determines the future of their company,

AD-A051 789 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO F/G 17/2.1
MILITARY DIGITAL MICROWAVE TRANSMISSION: PAST, PRESENT, FUTURE.(U)
AUG 77 R E BRACKETT, W E CARTER, J J SOLTIS

UNCLASSIFIED AFIT-CI-78-45 NL

2 OF 4
AD
A051789



its profit and loss, and the project engineer's reputation. Therefore, it was not surprising when the FCC issued Docket No. 19311, that the number of diverse replies were received with respect to the questions regarding (1) emitted spectrum and bandwidth, (2) cross polarization and spectrum allocations, and (3) interference between PCM/TDM-FM and FDM-FM systems.

In part, the absence of the necessary national and international standards and regulations helped to create the differences in view points, which for the most part, did have some parochial technical substance.

The important point to be made and realized is that, these things happen and because they do, there is usually an impact on the Industry and the Military.

With these thoughts in mind, the three problems that have played a dominant role in the formulation of the Military Digital Microwave Transmission Systems are examined further.

Emitted Spectrum and Bandwidth

It cannot be denied that, at the inception of digital modulation and up until recently, systems using forms of digital modulation had a lower spectral capacity than did systems employing FDM-FM modulation.

The limited spectrum resource had been divided up for frequency management purposes at the national and international levels as discussed earlier in this chapter. Consequently, Industry and the Military were faced with using the digital modulation technology in confined portions of

the spectrum which restricted bandwidths. This is exemplified on an international basis by the problems encountered by the Military in implementing the FKV System Upgrade in the Federal Republic of Germany.

As mentioned earlier in this Chapter, Competition for the Radio Spectrum, the U.S. Military had agreed to vacate th 2 GHz microwave band within the Federal Republic of Germany (FRG). In agreeing to do so, the Military was assigned frequencies in the eight GHz band. Because not all of the U.S. Military communication requirements could be met within the existing military portion of the eight GHz band, the FRG agreed to share a portion of the band that had been allocated exclusively for German civilian fixed communications services.

In 1967, the FRG divided the shared spectrum into seven-MHz-channel pairs to accommodate the 120 VF channel U.S. Military FDM-FM systems that were predominant in the two GHz band.

Subsequently, in 1969, to accommodate the U.S. Military requirements for the 300 VF channel European Wideband Communications System (EWCS), the Federal Ministry for Posts and Telecommunications of the FRG assigned adjacent seven MHz channels to provide the required bandwidth of 14 MHz.

The U.S. Military, in 1973, requested frequencies to be used for the FKV System Upgrade. Since the system was to use the three-level partial response modulation technique of digital modulation, the Deutsche

Bundespost was asked how to measure the emitted spectrum to show conformance with the allocated bandwidth of 14 MHz. Their reply[27] cited the use of CCIR Report 378-1 titled "Radio-Relay Systems for the Transmission of Pulse Code Modulation and Other Types of Digital Modulation" as a guide, and that digital out-of-band emissions should be designed to cause no more interference to FDM-FM than FDM-FM to FDM-FM.

The CCIR Report 378-1 contains guidance as to the measurement of an emitted digital spectrum. Guidance had been established in CCIR Recommendations for the definition[28] and measurement[29] of amplitude modulated signals and frequency modulated signals, but the recommendations had not been updated to take digital transmission into account.

The U.S. Military after exhaustive testing, proceeded on the basis that an acceptable approach would be to show that 99% of the emitted power was contained in the allocated 14 MHz bandwidth. This was accomplished by numerical integration of the spectrum plots that offered the best trade-offs between digital and orderwire performance.[30] Scrambling and RF filtering were used to control the out-of-band emissions. An electromagnetic compatibility (EMC) analysis was used to satisfy the potential mutual interference problem between the U.S. Military system and the FRG civilian system.

To further the discussion of spectral capacity and bandwidth, it can be shown that three-level partial response (used by the U.S. Military on the FKV) and QPSK do not inherently provide a one-bit per Hertz

efficiency, but must be filtered to achieve it. This is shown in Figure 4-3.

The emitted spectrum for the unfiltered QPSK data rate of 20 Mbps is shown with the filtered spectrum. The unfiltered spectrum occupies 80 MHz of bandwidth with side lobes only down by 20 dB. This is certainly in support of the allegations that digital transmission is an extravagant user of the spectrum and further, it reduces the spectral efficiency to 0.25 bits per Hertz. With the use of a 20 MHz RF filter however, it can be seen that the side lobes, except the first side lobe, are well down and 99% of the emitted power is contained within 17 MHz of bandwidth for an approximate spectral efficiency of 1.18 bits per Hertz.

The spectral capacity of QPSK[31], with a spectral efficiency of one bit per Hertz, is 15 voice channels per MHz of singular polarized radio channel, only one fourth that of an FDM-FM system.

Filtering was not only necessary to increase the spectral efficiency of the digital transmission system, but it was also necessary to lessen the interference between it and the FDM-FM systems.

Interference Between Digital and Analog Systems

One of the major potential problems addressed by the FCC in the Docket No. 19311 Notice of Inquiry was that of interference between the proposed digital systems and the existing FDM-FM systems within the commercial and military microwave bands.

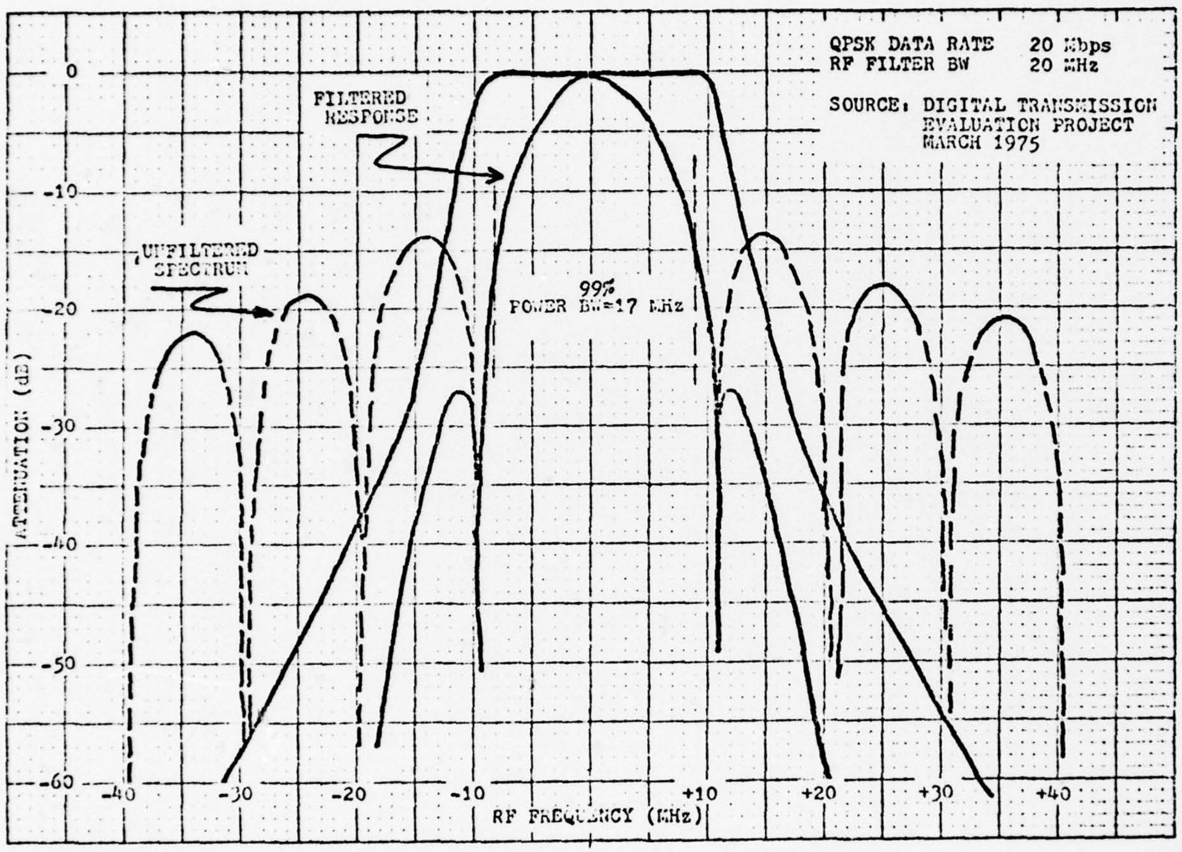


Figure 4-3. QPSK Emitted Spectrum.

Digital transmission systems[32] operate very successfully in the presence of high level interfering signals. This property is valuable in an all digital environment where systems can be packed closer together thereby partially compensating for extravagant digital bandwidth occupancy. The same strategies that work in an all digital environment are not tolerable when used in a mixed FDM-FM and digital environment.

Respondents, in their comments to the FCC for Docket No. 19311 were not in agreement as to the amount of interference that PCM/TDM-FM would present to the existing FDM-FM systems. Microwave communications Inc.[33] (MCI) and General Telephone and Electric (GTE)[34] were two respondents that claimed that not enough was known at the time (1970-71) about mutual interference, and that a study program should be carried out. In essence they felt that digital transmission should not be allowed in the microwave band below 15 MHz. (MCI's management and marketing philosophy are presented in Chapter Seven, Digital Transmission Systems).

On the other hand, the American Telephone and Telegraph Company (AT&T) in its Reply Comment, had cited eleven major equipment manufacturers who supported the use of digital modulation in the microwave bands below 15 GHz and further stated that:

> ...the technical arguments presented, while varying in analytical approach and limitation derived there-from, clearly show that digital and analog facilities can exist in the same bands under appropriate interference criteria and bandwidth emission standards.[35]

AT&T went on to imply that the MCI and GTE positions were directly

related to their stake in currently produced equipments which operate on the frequencies under consideration.

The Data Transmission Company (DATRAN) presented arguments[36] that were very much in favor of digital transmission in the microwave bands below 15 GHz, and went on to give practical evidence to disclaim the MCI and GTE comments. The DATRAN management and marketing philosophy is also presented in Chapter Seven.

Setting the emotional aspects of this question aside, there were indeed methods of calculating such interference. Methods were proposed by Nippon Electric Company (NEC), AT&T and DATRAN. An analysis of industry responses to Docket No. 19311 made by the Institute of Telecommunications Sciences at Boulder, Colorado concluded that

> Of the three, the most complicated was NEC's and the easiest was AT&T's. DATRAN's report included considerable measured data as well as a very good theoretical analysis which is compared with measured data.[37]

AT&T recommended that the digital spectral density outside the first nulls be kept at least 50-55 dB below the mid-channel spectral density.[38] Looking back at the comparisons of the digital and analog FM spectrums in Chapter Three, Figure 3-16, it can be seen that, if the FCC were to apply AT&T's recommendation the spectral density of the digital side lobes (out of band emissions) would be down 80 dB from the mid-channel spectral density of the FDM-FM system, and consequently, 10 dB below the out-of-band spectral density of the FDM-FM system.

This approach places a harsher technical restriction on digital transmission than that for FDM-FM and additionally increases the costs of the equipment by requiring a broadband filter with skirts steep enough to satisfy the AT&T recommendation.

Another method of controlling the power in the side lobes of a digital system was that of scrambling the digital signal to break up repetitive patterns that concentrated power within the spectrum.[39]

As mentioned earlier, the U.S. Military used scrambling and RF filtering on the FKV system to make it compatible with existing FDM-FM systems by containing 99% of the emitted power within the allocated 14 MHz.

It was fairly well concluded that digital systems and FDM-FM systems could co-exist with proper safeguards, but questions concerning extravagant use of the spectrum and the spectral capacity of digital systems were still present.

Cross Polarization and Spectral Capacity

Cross polarization is technically feasible and has been demonstrated in the laboratory and over test microwave links at 11 GHz[40,41] and higher.[42,43] Tests at these frequencies have shown that severe cross polarization isolation degradation was experienced when the primary feed aperatures became wet during rain or snow storms[44] (i.e. 9-10 dB cross polarization isolation during wet conditions compared to 45 dB during normal conditions). A significant amount of cross polarization isolation

was maintained when the antennas (apertures) were protected during heavy rainfall with the use of radomes or shrouds.

Digital transmission's inherent immunity to interference makes the use of cross polarization technically attractive thereby increasing the spectral capacity.

Early attempts to make the digital spectral capacity comparable to the FDM-FM spectral capacity made use of cross polarization. It was argued[45] that, by using a digital modulation technique that was two bits per Hertz spectrally efficient and cross polarization, that a digital transmission system would have a spectral capacity comparable to FDM-FM.

This was in fact, an unfair comparison because FDM-FM systems could not capitalize on the inherent interference immunity of the digital transmission system. The FDM-FM system could therefore not employ cross polarization to the same advantage in doubling its information carrying capacity. In the past, polarization has been used in FDM-FM systems, when in close proximity, as a frequency management tool to suppress intersystem or co-channel interference.

The advocates for digital microwave transmission were in essence, using two frequency assignments when comparing data capacities of the systems.

In conclusion, the reader should bear in mind that the emitted spectral efficiency of either system should be related to the value of the information being transmitted.[46]

Which Way to Turn?

Given the political, regulatory, technical, and economic problems discussed in this chapter, the Military was faced with making several decisions.

The FKV was only an interim solution to the Military's all digital Defense Communications System. What the Military needed next was, (1) answers to the technical questions raised by the respondents to FCC Docket No. 19311, (2) an in-depth knowledge of the microwave digital modulation techniques, and (3) a determination of what digital transmission equipment was currently available, and whether or not it was suitable for the Defense Communications System.

Consequently, the Military performed a survey of digital transmission equipment which is presented in Chapter Five, and instituted test facilities and test beds, which are described in Chapter Six, in an effort to establish a much needed data base concerning the available equipment and its performance. Additionally, as described in Chapter Seven, the Military studied the existing commercial digital transmission systems and philisophies for possible Military application.

CHAPTER 4

Footnotes

1. The Federal Communications Commission, Notice of Inquiry: Docket No. 19311, released September 15, 1971, p. 3. An example of this is a 192 voice channel PCM/TDM system requiring 12.6 Mbps. The above techniques would require RF bandwidths of approximately 25 MHz and 14 MHz. Compared to the 7 MHz necessary for a 192 voice channel FDM-FM system, these techniques suffer from more than a three fold and two fold disadvantage.

2. Defense Communications Engineering Center, Digital Transmission System Design Technical Report No. 3-74, March, 1974, p. D-1.

3. Defense Communications Agency letter, 470, "DCS Digital Microwave Radio, PCM and Digital Multiplex," dated 23 June 1973.

4. Office of Telecommunications Policy, Manual of Regulations and Procedures for Radio Frequency Management, Executive Office of the President (Revised May 1977), p. 3-1.

5. Donald O. Schultz, "DCS Transmission Network: 1980-82," Conference Record, 1976. International Conference on Communications. Vol. II, June 14-16, 1976, Philadelphia, p. 33-12.

6. Office of Telecommunications Policy/Interdepartment Radio Advisory Committee, Report for the Period January 1-June 30, 1976, p. 2-3.

7. Ibid., p. 2-3.

8. Electromagnetic Compatibitliy Analysis Center. Annual Report 1976, p. 3.

9. Defense Communications Engineering Center, Digital Transmission System Design: Technical Report No. 3-74, March, 1974, p. D-6.

10. United States General Accounting Office. Information on Management and Use of the Radio Frequency Spectrum-A Little-Understood Resource. Sept. 13, 1974, p. 41-43. The OTP created a Career Development Program for Radio Spectrum Management in July 1975 and set forth the guidelines and policy with OTP Circular No. 14, dated August 21, 1975. The program is designed to fill the manpower gaps and increase the professionalism required to perform this delicate mission.

11. Office of Telecommunications Policy, Activities and Programs 1975-1976. Executive Office of the President, p. 25.

12. The Radio Frequency Spectrum: United States Use and Management. Office of Telecommunications Policy (January 1973), p. C-10.

13. Manual of Regulations and Procedures for Radio Frequency Management. Executive Office of the President, Office of Telecommunications Policy, (Revised to May, 1977), p. 1-6.

14. Ibid., p. C-16.

15. Harold T. Dougherty and Ernest K. Smith, "The CCIR and Radio Propagation-A Mini-Review." IEEE Transactions on Antennas and Propagation, November 1976 , pp. 910-912.

16. Ibid., p. 911.

17. The Federal Communications Commission, Docket No. 19311, Notice of Inquiry (September 15, 1971), p. 3.

18. Ibid., p. 1.

19. The Federal Communications Commission, Docket No. 19311, Order (December 13, 1971), p. 1.

20. The Federal Communications Commission, Docket No. 19311, Notice of Proposed Rule Making (May 8, 1973), pp. 71:143-71:155.

21. Telecommunications Technical Memorandum, An Analysis of Industry Responses to FCC Docket 19311 Relating to The use of Digital Modulation on Microwave Radio Links, U.S. Department of Commerce (December, 1972), pp. 1-25.

22. Val. J. Williams, "Digital Modulation Techniques: Reply Comments of NABER," Action, VIII No. 1 (January, 1972), p. 10. The National Association of Business and Educational Radio (NABER), Executive Vice President and General Manager (Val. J. Williams) wrote comments to comments of the Aerospace and Flight Test Radio Coordinating Council and the Fixed Point to Point Communication and Industrial Electronics Division of the Electronic Industries Association. He (Williams) offered no technical input, but did ask "that if further inquiry is made into the matter by the Commission, the matter be separated into two dockets: (1) one addressed to those rules applicable to common carriers, (2) one addressed to private microwave rules.

23. Gene Bylinsky, "DATRAN's Hazardous High-Wire Act." Fortune, February, 1976, p. 132.

24. Ibid., pp. 132-133. DATRAN's owner Wyly thought AT&T might continue to neglect the advanced technology, leaving DATRAN ample opportunity to attract customers dissatisfied with the quality of Bell service. Penisten, (Engineer) on the other hand, was certain that AT&T would try to innovate its own and try to run DATRAN out of business.

The response came sooner than even Penisten had expected. "In October, 1972, AT&T filed an application with the FCC to use some microwave channels, just below the voice band, for digital transmission of data."

25. Ibid., p. 134.

26. The Federal Communications Commission. Notice of Proposed Rule Making: Docket No. 19311 (adopted May 3, 1973, released May 8, 1973), pp. 71:143 to 71:162.

27. Federal Ministry for Posts and Telecommunications letter to United States European Command dated October 2, 1973. Subject: Microwave Radio-RF Bandwidth.

28. International Radio Consultative Committee. "Recommendation 328-2: Spectra and Bandwidths of Emissions." CCIR XIIth Plenary Assembly, New Delhi, 1970. Vol. I, pp. 39-49.

29. International Radio Consultative Committee. "Recommendation 327-2: Measurement of Spectra and Bandwidths of Emissions." CCIR XIIth Assembly, New Delhi, 1970. Vol. I, pp. 35-39.

30. J. E. Farrow and R. E. Skerjanec. AN/FRC-80(v)3: Retune and Time Division Multiplex Interference Investigation. Department of Commerce/Office of Telecommunications, October, 1974, pp. 57-116.

31. Frank S. Boxall. "Digital Transmission via Microwave Radio: Part II." Telecommunications, April 1972, p. 48.

32. Ibid., p. 61.

33. Microwave Communications Incorporated. "Comments of the MCI Carriers Carriers to Docket No. 19311," November 15, 1971, pp. 5 and 6.

34. General Telephone and Electric Company. "Comments of GTE Lenkurt Incorporated to Docket No. 19311," November 15, 1971, pp. 3 and 4.

35. American Telephone and Telegraph Company. "Reply Comments to Docket No. 19311," January 17, 1972, p. 5.

36. Data Transmission Company. "Reply Comments of the Data Transmission Company (DATRAN)," January 17, 1972, pp. 5 through 8.

37. J. E. Farrow. "An Analysis of Industry Responses to FCC Docket 19311 Relating to the Use of Digital Modulation on Microwave Radio Links." Office of Telecommunications Sciences, Office of Telecommunications, U.S. Department of Commerce, December, 1972, p. 16.

38. Ibid., p. 16.

39. Boxall, op. cit., p. 48.

40. P. A. Watson. "Attenuation and Cross Polarization Measurements at 11 GHz." Proceedings of the IEEE International Conference on Communications. June 1972, Philadelphia, pp. 2-21 through 2-24.

41. P. A. Watson, S. G. Hobrail and F. Goodall. "Mutual Interference Between Linear Crosspolarized Radio Channels at 11 GHz." Electronics Letters (July 1, 1971), Vol. 7, No. 3, pp. 374 through 377.

42. Morton J. Saunders. "Cross Polarization at 18 and 30 GHz due to Rain." IEEE Transactions on Antennas and Propagation, March, 1971, pp. 273-277.

43. David T. Thomas. "Cross-polarization distortion in microwave radio transmission due to rain." Radio Science. Vol. 6, No. 10, pp. 833-839.

44. Watson, et al., op. cit., p. 374.

45. Boxall, op. cit., p. 48.

46. Ibid., p. 44.

CHAPTER 5

INDUSTRIAL SURVEY OF DIGITAL TRANSMISSION HARDWARE

Having discussed some of the current digital modulation techniques, and the various political, regulatory, and technical problems involved in the design and implementation of a digital microwave transmission system, the results of various industrial surveys are presented to reflect the commercial market of available FM and digital radios.

Hardware Posture and Technology

The digital transmission system integration into the DCS required a study of available hardware techniques to complement the Military's technical knowledge base during the planned test and evaluation programs. The DCS & MILDEP objective then, was to build an in-house capability for implementing a practical digital microwave transmission system which could be operated and maintained adequately on a worldwide basis.

The industrial survey presented is a result of various separate efforts. The first survey of FM and digital radios was performed by Microwave Systems News (MSN) in 1973. The purpose of that survey was to provide a look at the expansion of the radio manufacturing segment

of the industry into new modulation techniques. The MSN survey, Table 5-1, reflects the radio capabilities available during the time frame of the Military digital test beds. Table 5-2 reflects the current industrial survey as prepared by the Digital Transmission Evaluation Program (DTEP) in 1975-1976, to include both national and international equipments. Subsequently, entrees are provided to reflect the state of the art in digital radios which resulted after the 1976 update survey. Other survey information performed by various agencies is also included in these Tables.

Hardware Matrix

The matrix approach was found to provide a useful, tabulated look at equipment specifications as taken from the manufacturer's technical equipment summaries. The Table 5-1 matrix indicates the available equipments were restricted to the frequency range of 11 GHz and below. Some video transmission capability was available in the 12-13 GHz range but is not reflected in the Tables. The modulation schemes were primarily FM, with several radios, such as the Avantek DR2A-T1, employing digital modulation.

Table 5-2 is an updated survey of industrial hardware which shows an increased flexibility and capability in industry. Some of the present capabilities of these radios are discussed below. OKI Electric of America has an 18GP series of digital radios which operate in the 17.7-19.7 GHz frequency band. The 18 GP series consists of three

Table 5-1

MICROWAVE SYSTEMS NEWS RADIO EQUIPMENT SURVEY

Equipment Vendor	Model or Equipment Number	RF Frequency Range (GHz)	Minimum Transmit Power	Circuit Channel Capacity (SSB-SC)	Receiver Noise Figure (dB)	Notes
Avantek	DR2A-T1	2.0	1W	2 T1 PCM	6	QPSK
Farinon	SS2000W	2.0	3.2W	300	8	Fixed Service
Microwave Associates	MA-2H	2.0	8W	Video	9.5	Solid State IF (Heterodyne)
Motorola	MR-200	2.0	4W	348/600	9	
Collins	MS-109E	4.0	5W	960/Video	12	
Farinon	SS-4000 Series	4.0	2W	300/600/960/Video	9	
GTE	7562	4.0	8W	1200/Video	8	
Raytheon	KTR3A-4	4.0	1W	960	11	
Collins	MW-318A	6.0	1W	120/420/300	9	
Microwave Associates	MA-7B	6.0	0.6W	1200/Video	11	
Motorola	MR-600	6.0	0.6W	480/960	9	
OKI	6GB960	6.0	1W	960	6.5	
Raytheon	KTR3E	6.0		1800/Video	9.5	
Collins	MW-618	11.0	0.3W	120/300/600/960 1200/Video	10	
Microwave Associates	MAV-12D	11.0	1W	1152 PCM	9.5	

Table 5-2

DIGITAL TRANSMISSION EVALUATION PROGRAM SURVEY 1975-76

Equipment Vendor	Model or Equipment Number	RF Frequency Range (GHz)	RF Power Output	IF Frequency (MHz)	Modulation Technique	PCM Voice Channels per Polarization
Avantek	DR 2C-48	1.7-2.3	1W/100mW	70	QPSK	24
Avantek	DR 2C-96	1.7-2.3	0.5W/100mW	70	QPRS	96
Canadian Marconi	MCS-6900 series	1.7-2.3 6.575-6.875 7.125-7.850	3.2W 0.8W 0.5W	70 70 70	8-Level FM	120
Collins	ARPA Packet (Experimental)	1.710-1.850	10W	298	MSK	288
GTE Lenkurt	78F2 and 9120A	1.7-2.3	5W			48
Farinon	DMI-2A	2.1-2.2	0.5W	21.4	QAM	96
Collins	AN/FRC-155 thru 160	4.4-5.0 7.125-8.400	0.5W 5W	70	QPSK	288
Collins	MDR-6	5.925-6.425	10W	70	8 PSK	1344/90 Mbps
Nippon Elec. Company	TP-6G44MB-1A	5.925-6.425	5W	70	8 PSK	
Raytheon	RDS-60	6	10W	70	8 PSK	1344/90 Mbps
Communications Carrier, Inc.	ICM-7 ICM-7080	7-8.5	Variable to 1W	120	Modifiable to QPSK	576
Communications Carrier, Inc.	MCT-7 MCT-15	7-8.5 15	1W	120	FM	288
Raytheon	RDS-80G	7.125-8.4	1W		Differential QPSK	312/20 Mbps

Table 5-2 (cont)

Equipment Vendor	Model or Equipment Number	RF Frequency Range (GHz)	RF Power Output	IF Frequency (MHz)	Modulation Technique	PCM Voice Channels per Polarization
Raytheon	RS-840	7.125-8.4	1W		QPSK	140 Mbps
Raytheon	RS-842	7.125-8.4	1W	70	QPSK	600
Raytheon	RS-1040	9.5-10.7	1W		QPSK	140 Mbps
Collins	MDR-11 MDR-11N	10.7-11.7 10.7-11.7	10W 10W	70 70	8 PSK 8 PSK	1344/90 Mbps 672/44 Mbps
Microwave Associates	MA85TV-12D B-Line/11-Series	10.7-11.7 5.9-12.2	1W	70	QPSK/QPRS FM/PCM	696/1200 1200/288
Nippon Electric Company	TP-11G44MB-1A	10.7-11.7	5W	70	8 PSK	
Raytheon	RDS-80	10.7-11.7	1W	70	QPSK (Coherent)	600/40 Mbps
Martin Marietta	GRC-200	14.4-15.25	100mW			600
OKI Electric of America	OKI 18GP-100 Mbps	17.7-19.7	30mW/100mW	2GHz	QPSK	1344
OKI Electric	OKI 18GP-200 Mbps	17.7-19.7	30mW/100mW	2GHz	QPSK	2688
OKI Electric	OKI 18GP-280 Mbps	17.7-19.7	30mW/100mW	2GHz	QPSK	4032
OKI Electric	OKI 20GP-400Mbps	17.7-19.7	0.25W	1.7GHz	QPSK (Differential)	
Norden Telecom.	2201-2206	21.2-23.6	50mW		FSK	96 PCM
Norden Telecom.	3901-3906	38.6-40	25mW	20	FSK	96 PCM
OKI Electric	OKI 40GP-1.5/6.3 Mbps	38.6-40	20mW/60mW	320	Double Phase QPSK	96

radios which are capable of handling 4,032, 2,688, 1,344, PCM voice channels. OKI also has a digital (40 GP) radio operating in the 40 GHz band, capable of carrying 96 PCM voice channels.

Microwave Associates' B-Line/11-series digital radio operates between 5.9-12.2 GHz, and is capable of switching between twelve pre-set crystal controlled frequencies thereby providing a much desired quick-tune capability. The radio can carry 288 PCM voice channels, and is suitable for emergency restoration applications.

Raytheon's RDS-80 digital radio is all solid state utilizing QPSK modulation and operating in the 11 GHz band. It is a completely modular microwave digital radio capable of handling high-speed time division multiplexing up to 80 Mbps through the use of cross polarization. It can accept digital inputs directly from PCM multiplex or T carrier lines. The Raytheon 6 GHz RDS-60 Digital Radio provides an increased capability by utilizing 8 PSK modulation as opposed to QPSK modulation. This radio has the inherent advantage of being able to replace 6 GHz analog radios, thereby enabling usage of existing facilities. Both the RDS-80, and the RDS-60 are suitable for backbone microwave relay on long haul systems.

Collins Microwave Division has developed the MDR-11 all solid state digital microwave radio which operates in the 10.7-11.7 GHz common carrier band, and uses 8-PSK modulation. It can handle 1344 channels within an allocated bandwidth of 40 MHz, or the equivalent of two DS-3 (44.736 Mbps) signals.

It should be kept in mind that these equipments were engineered to provide a specific commercial service. In practice, not all communications users can effectively utilize these advanced radios. The Military Departments, in their evaluation of PCM/TDM equipment for the DCS, decided to use an off-the-shelf interim approach to digital system integration. When the Defense Communications Engineering Office and the National Security Agency established the NSA Test Bed in July of 1971, most of the surveyed digital equipment and capability listed in the tables was not available, even on a prototype basis, for evaluation by the Military. As a consequence, the Military began its test and evaluation program with an interim solution in mind, i.e., to develop a means for transmission of digital data over field proven and readily available analog radios and multiplex. Chapter Six discusses these initial test and evaluation efforts by the MILDEPS and other government agencies, to satisfy the requirements for an interim digital transmission system, and the subsequent transition to an all digital DCS.

CHAPTER 6

DIGITAL TRANSMISSION EVALUATION

Thus far, the motivations for digital transmission, the modulation techniques, the regulatory aspects and problems encountered, and the national and international levels of industrial activity have been examined. The next logical step for the military to take was to gain first hand knowledge of the available equipments and their suitability for inclusion in the military fixed plant communications systems through the performance of tests and subsequent analysis of the test results.

During the spring of 1971 it was clearly apparent that the Military had not been and was not in a position to utilize digital transmission, since they lacked the requisite depth in digital technologies and knowledge of state-of-the-art digital transmission equipments. This lack would prohibit them from proceeding from the technical requirements to the implementation of a digital transmission system. Emerging from this realization was the desire immediately to learn more about the different digital transmission modulation techniques and those digital transmission equipments which various electronic radio manufacturers currently had in prototype and production states. The authority to do this was given by Defense Communication Agency Circular (DCAC) 330-195-2, Evaluation

of Selected Commercially Developed Equipment and Software, which provides for the acquisition, test, and evaluation of off-the-shelf commercially available equipments.

As a result of the situation described above, numerous tests were performed by various military departments and agencies with favorable and encouraging test results. This subsequently led to the continuation of some tests of particular significance which in turn encouraged the development of formalized test facilities. This section examines the significant objectives and the activities of four of the various test facilities which were established.

Tests and Test Facilities

Defense Communications Engineering Office (DCEO)/National Security Agency (NSA)

The application of PCM/TDM in the near-term Defense Communication System necessitated a planning and engineering phase for its future implementation. In support of this objective, a PCM/TDM System Design Verification Test Program was established at Fort Meade, Maryland from the period July 15, 1971 to January 1, 1972. This was to be a joint effort of DCEO NSA, and the Military Departments (MILDEPS). The purpose of the test program was to evaluate commercially available systems utilizing digital multiplex equipment, standard FM radio, and existing encrypting equipment for suitability in the DCS. Such an "off the shelf" equipment approach, would prove system feasibility,

without the usual extensive development and test periods.[1] The initial testing was to address a low density, 192 channel interim digital transmission system which could be implemented in the immediate future. In this endeavor, a digital microwave radio using four different digital formats, PCM multiplex equipment, and voice encoding equipment was utilized in various system configurations.

One of the PCM/TDM System configurations for the test is shown in Figure 6-1. The 24, 4 KHz voice channels were converted to digital form using PCM, Time Division Multiplexing, and encryption by the CY-104 equipment. The 1.544 Mbps output was time division multiplexed again with up to eight like channels to produce a multiplexed 12.6 Mbps signal. This signal was then combined with the service channel to form a composite baseband to drive the FM Radio modulator for transmission over the radio link.

The AN/FRC-80 (Motorola MR-300) microwave radio was used for this test in a modified state. It operated in the 8 GHz frequency range with a baseband frequency response of 10 MHz, flat within ± 3 dB, and Automatic Frequency Control (AFC) to maintain frequency stability. The transmitter amplified the input baseband signal with a modulation amplifier to provide the signal level to vary the carrier. The amplified baseband carrier was applied to the reflex klystron to modulate the 8 GHz carrier. In reconstructing the transmitted baseband signal, the receiver used an Intermediate Frequency (IF) center frequency of 70 MHz, and selectable IF bandwidths from 10-26 MHz.[2] The system was tested in

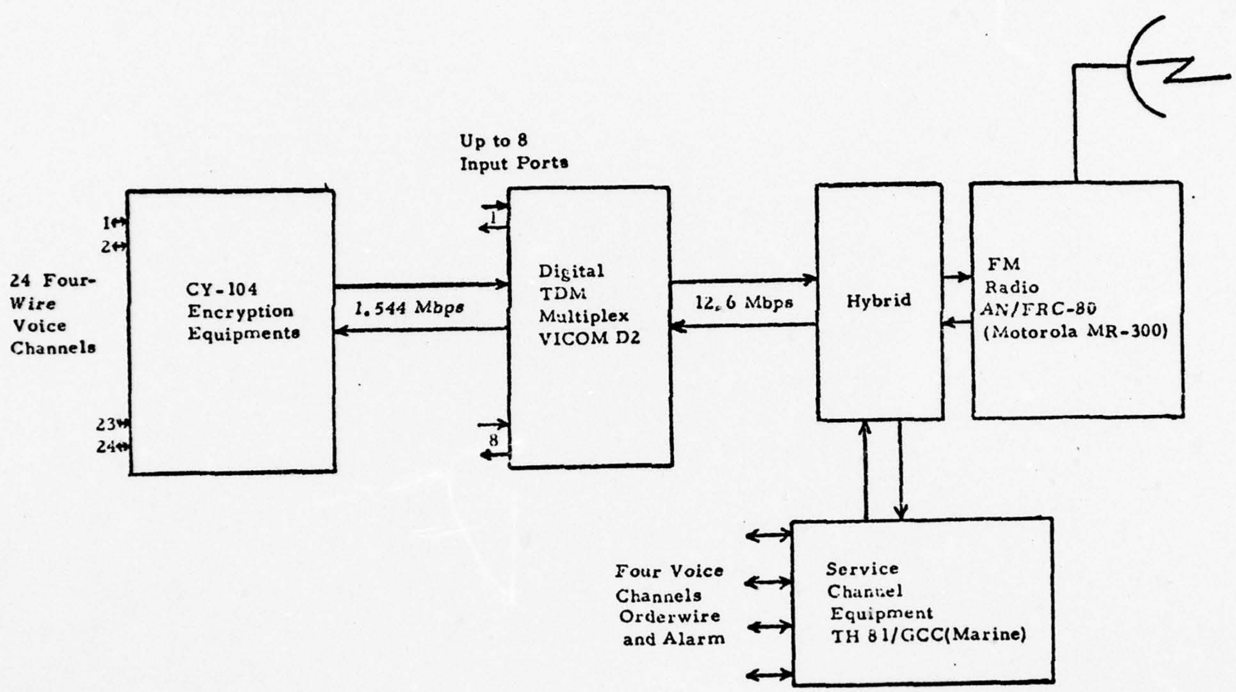


Figure 6-1. PCM/TDM System Configuration

three phases. The first phase evaluated radio to radio performance. The second phase added Time Division Multiplexing to the system configuration. The final phase introduced voice channel encoding which provided the desired system. The voice encoding schemes evaluated were: (1) VICOM Three-Level Partial Response, (2) Non-Return-to-Zero (NRZ), (3) Bipolar, and (4) IBM Three-Level Partial Response.

The error rate versus received signal level and the RF spectrum requirements of each scheme were measured for frequench deviations set from one to seven Megahertz (MHz), and Intermediate Frequency (IF) bandwidths of 10, 16, 20, and 26 MHz. A pseudo-random generator produced 12.6 Mbps of NRZ, Bipolar, and Three-Level Partial Response digital bit streams. The companion generator at the receiver contained a built-in error detecting and counting capability. A variable RF attenuator at the receiver simulated signal degradation in one decibel (dB) steps. The transmitted RF Spectrum requirement for the various frequency deviations was analyzed to determine the deviation which satisfied the 14 MHz, 99% power bandwidth RF spectrum limitation. To determine the best error performance of the four techniques, the RF spectral photographs of the "eye patterns," and the Bit Error Rate (BER) versus Received Signal Level (RSL) were compared. A three-level violation monitor using clock timing offset on the eye pattern sampling was evaluated as an indicator of system degradation. Tests were also performed to determine orderwire performance when tested with the VICOM 8-port TDM operating through an AN/FRC-80 (Motorola MR 300) radio link.

Test Results. The test error rate versus received signal level (RSL) showed similar results for all digital signal types. Significant errors did not occur until the received signal level dropped to -66 to -71 dBm. Best error rate vs. RSL performance was realized with the NRZ coding technique, but with greater RF spectral bandwidth.

Examination of the transmitted RF spectrum showed that IBM Three-Level Partial Response produced the narrowest emitted spectral bandwidth using a frequency deviation of 3 MHz. In determining the optimum deviation to meet the 14 MHz, 99% power bandwidth RF spectrum limitation; however, the 12.6 Mbps VICOM Three-Level Partial Response at 3 MHz deviation also met this requirement.[3] (Refer to Figure 6-2 below.)

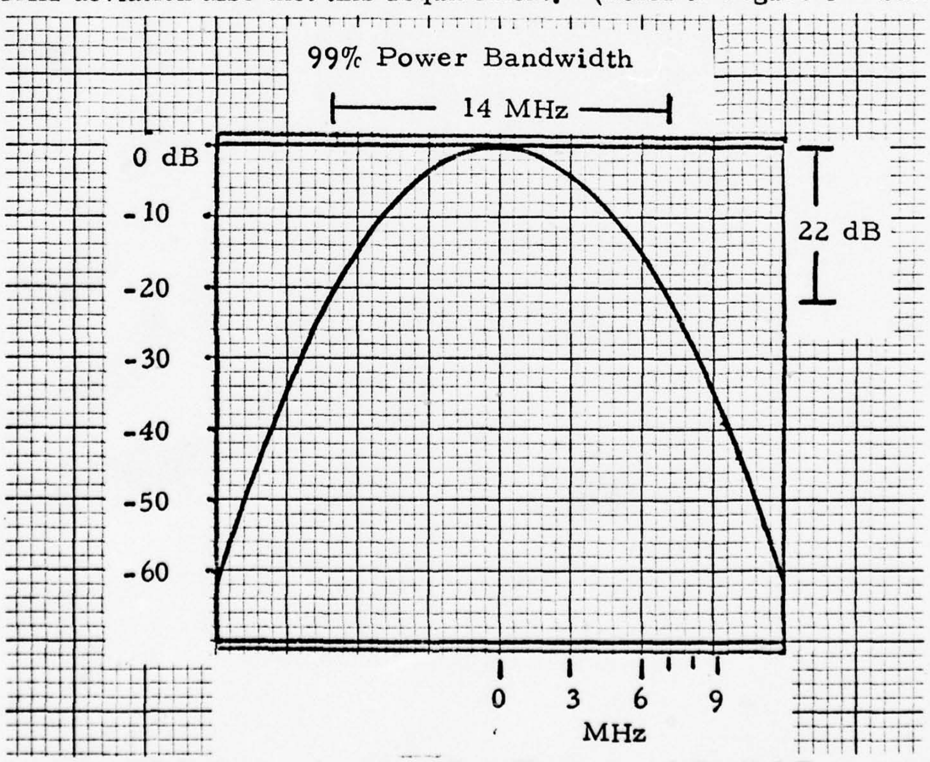


Figure 6-2. RF Spectrum for 12.6 Mbps Three-Level Partial Response (VICOM) Digital FM-3 MHz Deviation.

(Preliminary Report: PCM/TDM System Design Verification Test Program, Figure 4-35, p. 4-65.)

The photographs of the transmitted eye pattern and the received eye pattern showed that little noise and distortion degradation was added by the short, stable radio link to the 12.6 Mbps TDM signal. The results of these tests verified the acceptability of using Voice Frequency (VF) channel modems with a PCM/TDM digital FM System.[4]

The orderwire was defined as four 4KHz voice channels which had been frequency division multiplexed from 0-20 KHz. The Marine TH-81/GCC Telegraph-telephone terminal and TA-807/GCC telephone line unit were used as the orderwire hardware. The 8-port TDM was operated in two modes. The TDM was first operated with its built-in, duobinary filters as signal conditioners, and the orderwire was placed on an FM carrier located at the "high end" of the radio spectrum. The second mode bypassed the filters, and used bipolar encoding of the NRZ output of the 8-port TDM; thereby, allowing the placement of the order-wire at the "low end" of the radio spectrum. The results determined that for the "high end" orderwire, VICOM Three-Level Partial Response with an FM orderwire center frequency of 8-9 MHz, produced satisfactory performance (55dB Signal to Noise Ratio). Hardware complexity was reduced for the "low end" orderwire, and the bipolar data coding format resulted in consistently better performance, but at the cost of more RF bandwidth.

<u>Program Results</u>. The results of the DCEO/NSA test program established the technical feasibility of the near-term introduction of PCM/TDM into the DCS. The tests established the requisite design

integration of PCM, TDM, Digital FM Radio, PCM/TDM/Crypto Synchronization, Service Channel, and Modems for the proposed digital transmission system. Performance of these tests also established a definite need for Operation and Maintenance (O & M) procedures and manuals.

Some background system engineering for O & M had been previously done by the common carriers, notably the Bell Telephone System. In response to the growing military requirement for O & M standardization, the Air Force Communications Service (AFCS) was later tasked by DCA to perform detailed system integration and development of necessary O & M procedures for use by the MILDEPS. In keeping with the Military's "fix before failure" philosophy,[5] a means to detect early system degradation by monitoring certain key performance parameters in the system, such as sampling offset of the "eye pattern," was developed and found to provide a margin of 8-10dB (RSL) between the onset of measureable link degradation, and the start of a significant error rate in the digital bit stream. Refer to Figure 6-3. It should be noted that this was an initial approach to a problem which still exists today; that of predicting digital system performance degradation.

Additionally, it was concluded that a follow-on program for engineering and installation (E & I) principles for signal bulk encryption be promulgated by NSA.[6]

In conclusion, the test results were quite favorable, indicating technical feasibility through the use of several modulation schemes, and

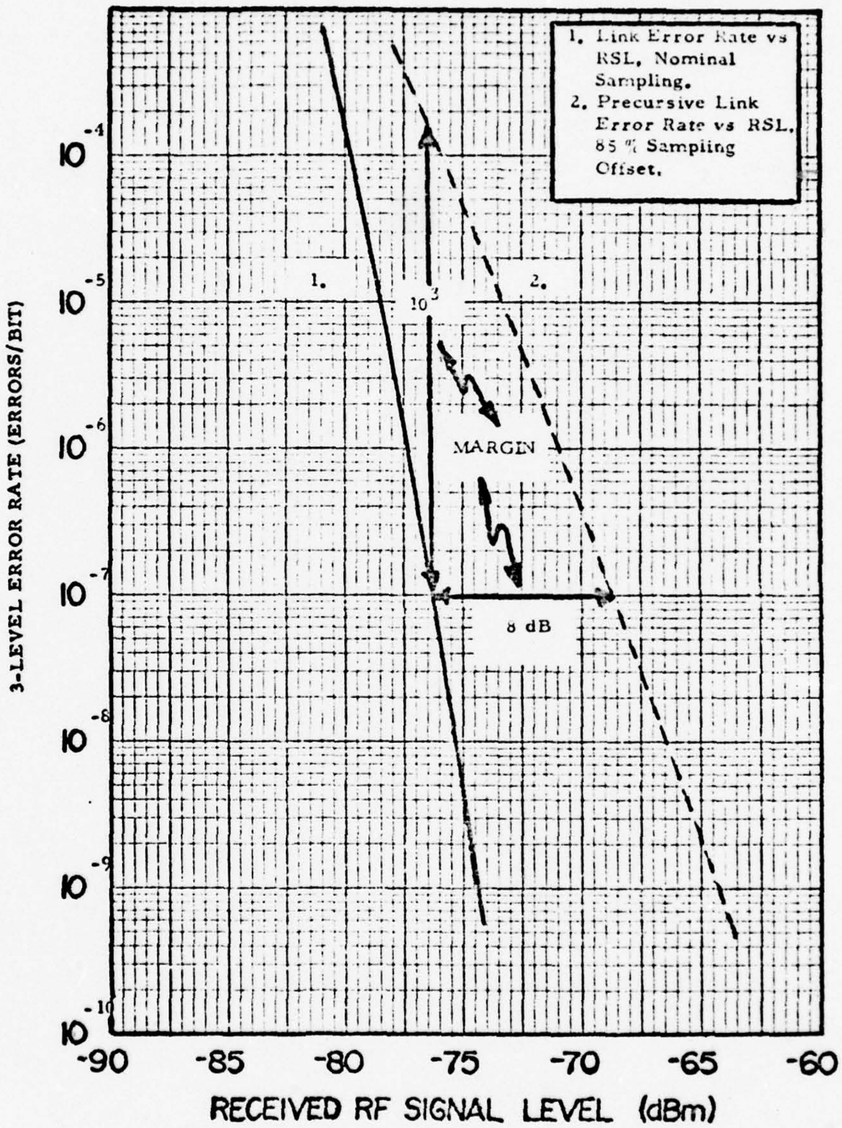


Figure 6-3. Digital Radio Link Margin Assessment
(Source: Preliminary Report: PCM/TDM System Design Verification Test Program, Figure 7-6, p. 7-25)

providing insight into those areas requiring (1) standardization of equipment and testing, (2) equipment and system performance assessment, and (3) fault isolation.

Air Force Communications Service (AFCS) PCM/TDM Test Bed, Richards-Gebaur Air Force Base.

Purpose. Concurrent with the initiation of the DCEO/NSA test bed at Fort Meade, Maryland, the DCA, through the Air Force Chief of Staff, authorized AFCS to establish an operational test and evaluation of PCM/TDM equipments. To support this requirement, the AFCS established the PCM/TDM Test Bed at Richards-Gebaur Air Force Base. A test program was developed providing two test phases for the digital system analysis. Phase I consisted of test and evaluation of off-the-shelf digital transmission equipment which met DCS performance requirements, with a principle objective of developing confidence in system design. Immedaite efforts were focused on performance assessment, fault isolation, and technical management capability.[7] In this endeavor, testing was directed at optimizing FM radios for digital capability, verifying an overhead channel (service channel) capability, and interfacing with a 4 KHz voice channel.

Phase II (actually test phase numbering was no longer used after Phase I) continued Phase I testing to further include new equipment under development for the DCS as it became available. The final combined test results provided equipment performance specifications for the participating defense agencies.[8]

In support of the test objectives, the test plan included (1) test concepts, (2) objectives and methods for quality control, (3) operational direction, (4) installation, (5) Operations & Maintenance, (6) cutover, and (7) integration of PCM/TDM into the total DCS.

The test program was a consolidation of test requirements of the participating agencies (DCA, MILDEPS, NSA) to assure PCM/TDM meets the operational performance requirements of DCS, and that it can be supported by O & M units on a cost effective basis. Test results were compared with the data accrued in the DCEO/NSA test bed.

Testing. The Phase I test period was conducted from November 1971 through August 1972. A flow diagram of the total transmission channel is shown in Figure 6-4. Tests were performed to optimize the FM Motorola MR 300 (AN/FRC-80(V)3) radio, and the Philco-Ford LC-4 and LC-8 heterodyne radios, and to establish baseline data for further testing. It was felt that the heterodyne radio could facilitate a subsequent conversion to QPSK modulation with a 70 MHz IF interface required between the PSK modem and the radio. A 1.0 volt peak-to-peak baseband received signal level was required for the TDM input signal for proper deviation of the 70 MHz IF carrier in the LC-4 and LC-8 radios, and the klystron in the MR-300. After the baseband and IF amplitude levels were adjusted, a microwave link analyzer was used to align the IF of each radio. Problems were encountered in alignment of the IF in that numerous adjustment steps were required on the LC-4 and LC-8 radios with no technical manual

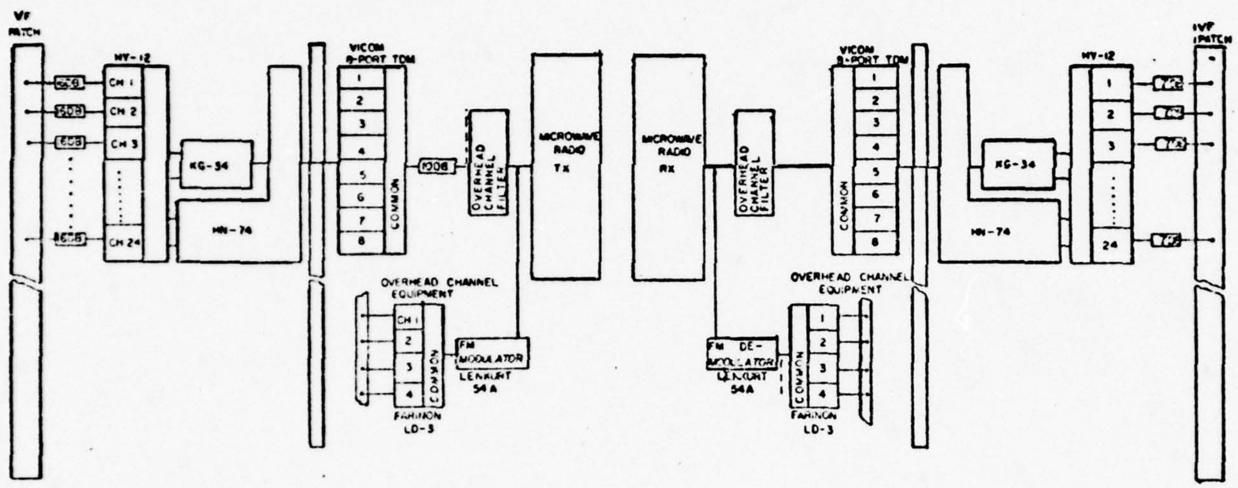


Figure 6-4. PCM/TDM Flow Diagram

(Source: DCS Operational Test and Evaluation of Pulse Code Modulation/Time Division Multiplexing (PCM/TDM) Equipment. Test Report August 1973- February 1974. Figure A1-2, p. A1-4)

BEST AVAILABLE COPY

sequence to follow, and in some cases, obsolete information in the manufacturers Technical Orders (TO's).[9] The RF frequency spectrum of the test radios was analyzed by varying Multiplex to Orderwire Baseband Ratios for various notch filters, and decreasing the microwave radio peak-to-peak frequency deviation. The latter procedure provided an additional means to adjust the spectral occupancy of the transmitted signal.

Orderwire and telemetry were provided using a four channel frequency division multiplexer which frequency modulates the overhead service channel on a 7.5 MHz carrier inserted in the TDM spectrum. The overhead service channel requirements dictated placing the channel above the TDM frequency range of 300 Hz to 6.3 MHz when using time division multiplexing equipment and three-level partial response. See Figure 6-5 Baseband Composite for the relative orderwire location in the frequency band. Before inserting the overhead service channel, 7.5MHz carrier, a 30 dB notch filter with a 7.5 MHz center frequency filtered a "notch" in the baseband signal, thereby removing any unwanted signal components.

Performance assessment of the communication system was evaluated to determine what parameters, when monitored, are valid indicators of system degradation. Figure 6-5 depicts the parameters available for monitoring at the various equipment interfaces. Experience at the test facility has shown that the microwave transmission channel is a principal factor in determining the end-to-end performance of a communications system. Degradation monitoring then becomes essential

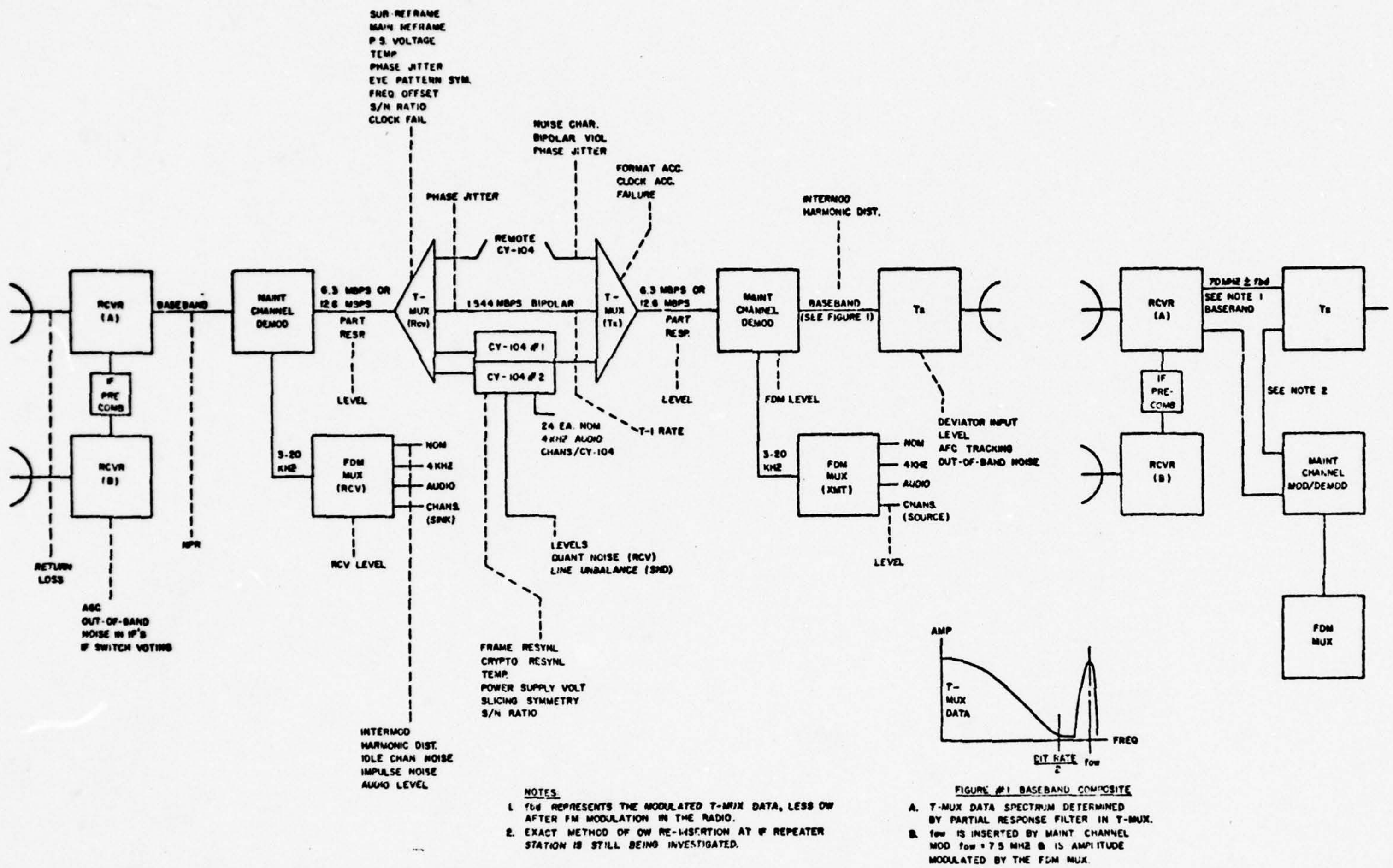


Figure 6-5. Performance Assessment Functional Diagram
(Source: DCS Operational Test and Evaluation of PCM/TDM Equipment, Phase I Testing Test Report, Figure 3.4-1, p. 111)

to prevent a system from reaching its threshold of usefulness, and doing so without limiting, or affecting normal system operation. The PCM/TDM test bed evaluated monitoring techniques for the VICOM 4000 and 8000 TDMs, to provide information for operations and maintenance personnel with regard to impending degradation, fault location, and probable cause of the problem. One method used in the evaluation was to develop an analog voltage which increases as the received signal departs from the ideal three-level partial response signal. By using a voltage comparator to slice the received signal at a level which detects one of the nominal basic modular waveforms, the interjection of noise will cause the signal to cross the voltage comparator reference level earlier than normal. Measurement of these time variations in relation to the nominal sample times will yield a quantity related to the degree of degradation present. This particular monitor technique does however, require the development of an adequate conversion circuit design to display the degradation on a ready visual reference, and a determination of the optimum slicing level for the detection process.

As an alternate method of monitoring the system performance, BER data was taken as a basis for comparison to the Degradation Monitor data.

The relative indication of a digital voltmeter (DVM) was used as the Degradation Monitor to measure SNR in dB as noise was introduced to the channel using a gaussian noise generator. Significant error rate

(10^{-7}) occurred when SNR decreased to 22 dB. (Reference Figure 6-6, TDM Signal Degradation Meter Indication.) Total useful range of the monitor was nearly 20 dB, and when compared with direct BER measurement, the Degradation Monitoring Circuit provided approximately 15 dB of advance notice to O & M personnel of system performance degradation.

One objective of the test and evaluation was to achieve a systems approach to maintenance.[10] To this end, the following requirements were listed as a part of this objective with changes permitted, depending on equipment configuration:

(1) The mean time required to perform on-site repairs must not exceed one hour (MTTR).

(2) The travel time (one-way) from the maintenance unit to the site will not exceed three hours.

(3) A site that has a possibility of being isolated from a remote maintenance unit for seven days or more will be manned by maintenance personnel.

(4) The Mean Time Between Failure (MTBF) of individual items of equipment should be at least five months.

The maintenance concept can be summarized as including the assignment of maintenance personnel to central maintenance work centers. On-site maintenance will consist of isolation and replacement of line replaceable units and system alignments. All remaining maintenance will be performed offsite. System parameter monitoring will be utilized to reduce the requirement for preventive maintenance. Finally, the following

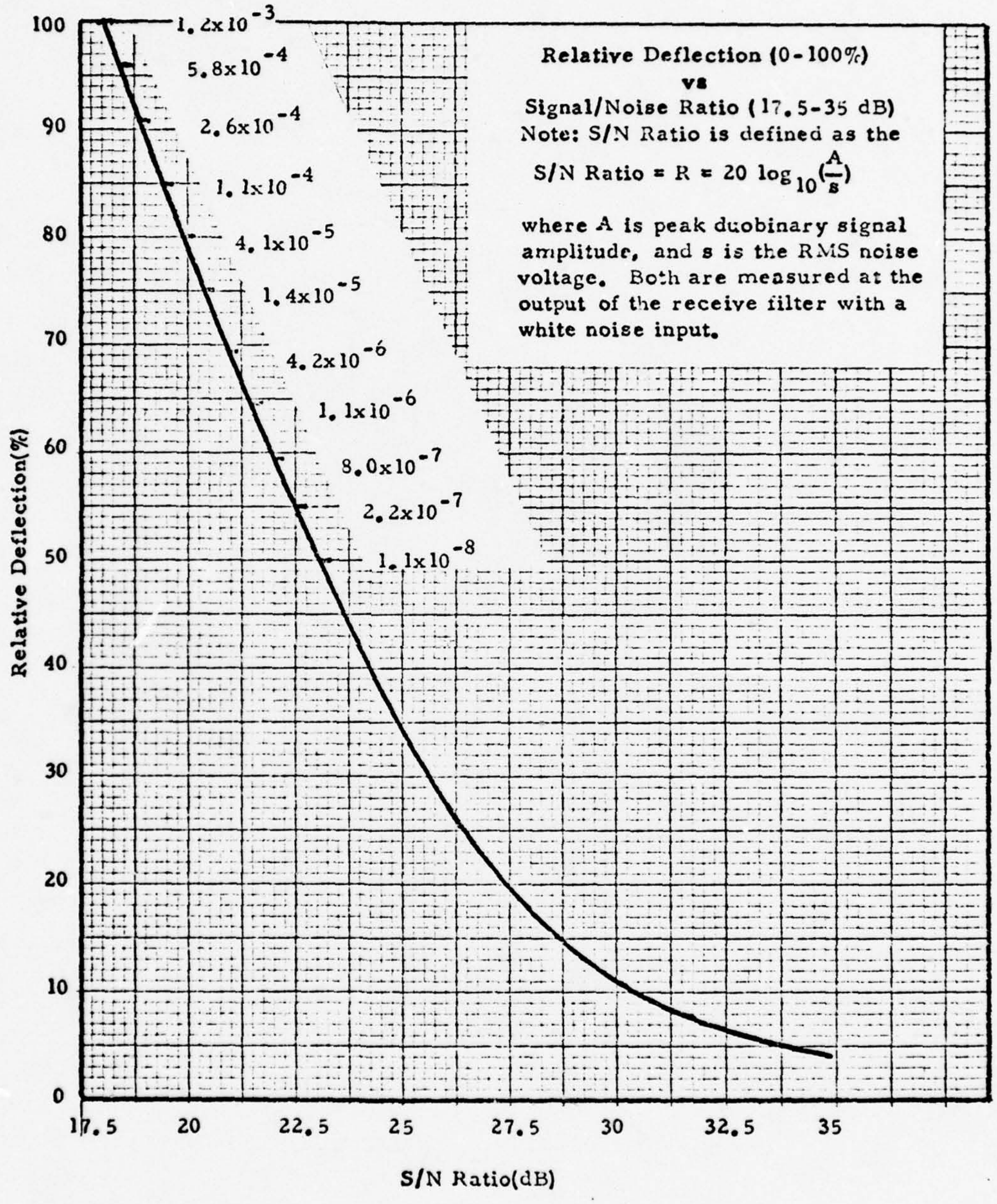


Figure 6-6. TDM Signal Degradation Meter Indication (Source: DCS Operational Test and Evaluation of PCM/TDM Equipment. Phase I Testing Test Report, Figure 5-12, p. 285)

documents form a part of the maintenance concept:

(1)	MIL STD 454C	Standard General Requirements for Electronic Equipment
(2)	MIL STD 1250	Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies
(3)	MIL STD 882	System Safety Program for Systems and Associated Subsystems and Equipments, Requirements for
(4)	MIL STD 1472A	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
(5)	MIL STD 471	Maintainability Demonstration Reliability Prediction
(6)	MIL STD 781B	Reliability Test: Exponential Distribution
(7)	MIL STD 757	Reliability Evaluation from Demonstration Data
(8)	MIL STD 721B	Definitions of Effectiveness Terms of Reliability, Maintainability, Human Factors, and Safety.
(9)	MIL STD 280A	Definitions of Item Levels, Item Exchangability, Models and Related Terms

Test Results. The conclusions of Phase I testing verified PCM/TDM equipment was installable within the DCS; however, certain TDM equipment interface access problems existed with the VF channels which prompted further evaluation. The test radios were able to accommodate a three-level partial response signal within bandwidth constraints, and operate essentially in a digital mode. Decreasing the modulation index of the FM radio improved the spectral occupancy, but at the expense of degrading the TDM signal. The overhead channel

insertion was still a problem area, with early attempts placing the orderwire outside the stipulated 14 MHz bandwidth, within which, 99% of the emitted power must be contained. It was further determined that amplitude hits, phase hits, and coincident hits would be the most viable indicator of VF channel activity indicating the system performance. Correlation is required against propagation anomalies.[11]

Phase II testing which followed immediately, continued with emphasis on system performance assessment techniques, determination of system degradation, and continued investigation of providing an acceptable overhead channel service.

This testing determined that such measurable parameters as idle channel noise, phase jitter, harmonic distortion, intermodulation distortion, crosstalk, and impulse noise, under normal conditions, provide a measure of VF channel quality in a PCM/TDM, as well as an FDM-FM System. Original AFCS test procedures established the Bit Error Rate (BER) as the common dependent variable to which all other parameter variations are directly related. Estimation of T-1 level BER (Figure 6-5) was obtained by measuring and recording the impulse noise counts and amplitude levels on an unused VF channel, but this technique did not predict system degradation.[12] While testing BER performance of the VICOM 4000 TDM, it was determined that small variations (1 dB) in the TDM received input signal level caused order of magnitude changes in BER. This was attributed to lack of gain stability in the Automatic Gain Control (AGC) amplifier. Disabling the AGC control voltage while

holding the three-level waveform input level constant at 1.0 volt peak-to-peak, improved the BER by three orders of magnitude. Further testing was recommended to determine a suitable degradation monitor.

The overhead service channel employed in the test bed which used a 7.5 MHz notch filter was not operationally acceptable because of bandwidth limitation. A 6.9 MHz filter however, did provide an acceptable RF bandwidth spectrum over a wide range of Multiplex to Orderwire Ratios (MOR) and within the FCC 14 MHz bandwidth limitation. Figure 6-7 illustrates the RF spectrum using a 6.9 MHz notch filter and a 6.9 MHz carrier for varying MOR. The higher MOR provides a narrower spectrum to remain within the FCC 14 MHz bandwidth restriction.

This method of providing a "high end" overhead channel was proven feasible, but pointed out an additional problem of linearity. The radios had to be more linear over a wider bandwidth to avoid the effects of intermodulation noise in the overhead channel. It was further determined that the overhead channel must be evaluated as part of the entire system, and not by a separate test as was done in the DCEO/NSA test bed.

In consideration of efficient O & M procedures, it was recommended that overhead service channels have the capability to "drop and insert" status and control information at unmanned repeaters. It was also recommended that the service channel be available in the event of transmission path failure. Since the overhead channel is inserted in the radio baseband, it is not available if the path fails or the system degrades. Therefore, alternate techniques, such as digital overhead channels, and

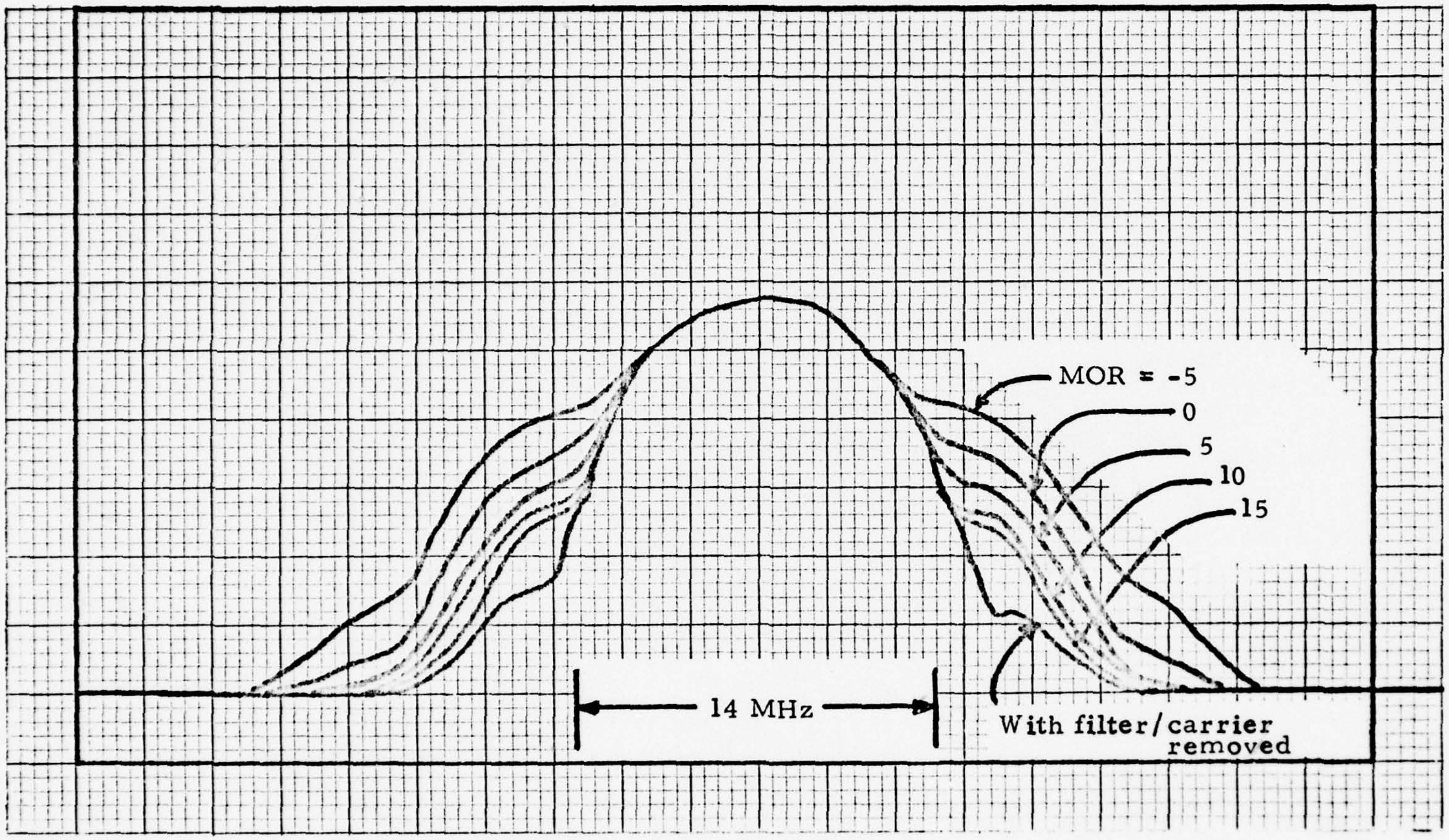


Figure 6-7. RF Spectrum Using a 6.9 MHz Notch Filter and a 6.9 MHz Carrier for *Various Multiplex to* Orderwire Ratios(MOR).

(Source: DCS Operational Test and Evaluation of Pulse Code Modulation/Time Division Multiplex Equipment. Figure 2-7, p. 2-13)

independent UHF/VHF subsystems, were suggested for subsequent evaluation.

Final recommendations for System Performance Assessment included further evaluation for determining equipment or system degradation in a predictive, rather than, after the fact, manner. The existing equipment performance indicators provided a partial digital indication of system performance. Additional analog type monitors were felt to provide timely information to predict service impairment and permit maintenance action prior to actual outage. These analog quantities could be monitored and passed to manned concentration points and maintenance centers using a sequential polling telemetry technique for display and imitation of necessary maintenance action.

The results of the digital test bed provided the guidelines for further digital transmission development. It was concluded that continued evaluation of the degradation monitor, overhead service channel insertion, and system performance assessment was required. Work accomplished at the test bed did however, lay the groundwork for Operations and Maintenance procedures to be used in the Digital European Backbone Program. AFCS is responsible for the Operational Test & Evaluation (OT&E) of the DEB program.

U.S. Department of Commerce/Office of Telecommunications/Institute of Telecommunications Sciences, Boulder, Colorado.

Since the results of the NSA tests were so favorable and since the DCS Microwave Radio Test Proposal Verification Model (TPVM) testing was being performed at the time by the Office of Telecommunications/ Institute of Telecommunications Sciences at Boulder, Colorado, the Defense Communications Agency (DCA) tasked the United States Strategic Communications Command in the late fall of 1971 (now the United States Army Communications Command) to perform digital transmission tests, utilizing a three-level partial response signal format, on each of the three candidate DCS Microwave Radios leased from the three bidders on the DCS Microwave Radio solicitation. Accordingly, the Office of Telecommunications/Institute of Telecommunications Sciences was requested to perform the three-level-partial response format tests upon completion of the requisite DCS Microwave Radio TPVM testing.

The broad objective of the tests was to determine whether or not the analog radios, which were designed to accommodate a frequency division multiplex derived, limited spectrum (12 KHz to approximately 3 MHz), low send and receive level baseband signal, could be adapted to operate as a digital radio carrying a time division multiplex derived spectrum (300 Hz to 10 MHz nominal, relating approximately to 12.6 Mbps) high send and receive levels. This was to be accomplished by determining whether the candidate DCS Microwave Radios would process the 12.6 megabit per second digital signals without undue degradation and to investigate

any modifications that might be required to fully adapt these radios for digital operation.[13]

<u>Digital Testing of the DCS Microwave Candidate Radios</u>. The tests were performed between 24 January 1972 and 1 February 1972, using a digital time division multiplexer driven by a pseudo-random generator and pattern comparator. A typical test configuration for the generation of the three-level partial response format is shown in Figure 6-8.

In order to pass the 12.6 megabit digital signal through the analog radios it was necessary to alter or remove various circuits and components to obtain optimum operation and to remove the supervisory baseband from the lower portion of the baseband spectrum. A synopsis of the basic modifications made to the radios for this testing is as follows:[14]

a. Disable the radio pilot and associated circuitry

b. Disable the squelch circuits

c. Remove or strapout attenuation networks

d. Remove or strapout the pre-emphasis and de-emphasis networks

e. Modify or by-pass the combiners

f. Reverse the output signal phase when out of phase with input signal.

g. Modify the wiring that was unique to TPVM configuration to obtain digital operation.

As previously discussed in Chapter Four, a major problem existed because current microwave frequency allocations are made in 14 MHz increments in some parts of the world. Obviously, if such a radio were to be

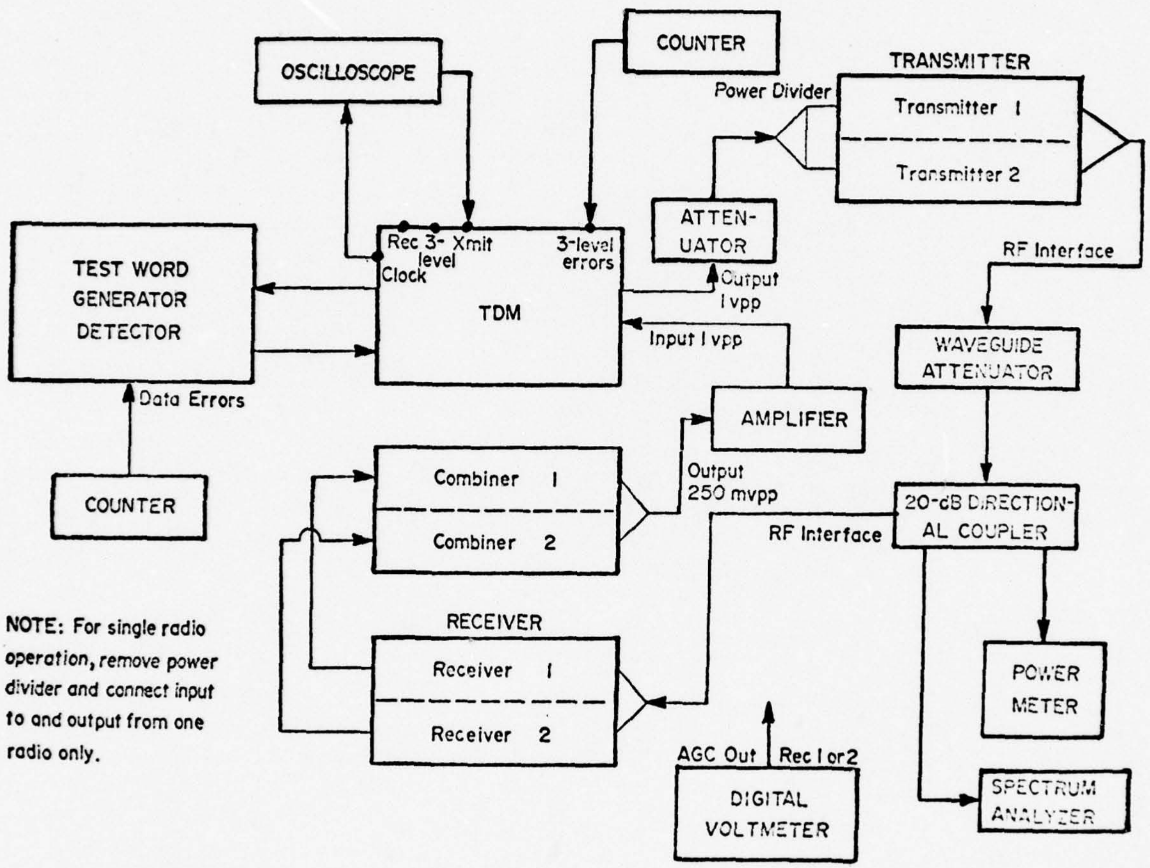


Figure 6-8. Typical Test Configuration for Three-Level Partial Response Format

fielded, it would have to be capable not only of interfacing with other equipments, but also capable of functioning within such a spectral allocation. Accordingly, the configuration and performance of each equipment was compared with the following criteria:

a. The transmitter emission spectrum must occupy no more than 13 MHz when loaded with the 12.6 Mbps signal

b. Nominal receiver IF bandpass must be at least 16 MHz

c. The baseband bandpass must extend from 300 Hz to 10 MHz.

<u>Test Results</u>. The tests were performed with peak deviation set at [illegible] MHz for all test combinations.[15] As a precaution, the receive signal level into the TDM was monitored at all times to insure that any errors observed were the result of radio noise caused by reduced recieved signal level as opposed to being caused by a low input signal voltage to the TDM. The input level to the TDM was held to one volt peak to peak.

The test results under these conditions included an indication of the receiver input signal level at which errors were first detected and the TDM alarms were activated. The data also included RF spectral photographs showing the distortion of the "Eye Pattern" photographed under various simulated conditions, and graphs depicting bit error rate versus receiver input level performance.

In general, errors were first detected within 7 to 8 dB of receiver noise threshold while the Sub-Reframe, Main-Reframe, Local, and Remote Alarms were activated with ± 2 dB threshold. A typical graph

showing Bit Error Rate as a function of Received Signal Level is depicted in Figure 6-9.

Analysis/Conclusions. The feasibility of transmitting a TDM derived spectrum of 300 Hz to 10 MHz (correlating to 12.6 Mbps or 192 channels) over an analog radio was clearly proven to be possible with only minimal design changes to the three different candidate DCS Microwave analog radios. Although this was easily accomplished on an engineering prototype basis, it should be borne in mind that to effect the same changes in production of these radios would be much more costly due to drawing changes, production processes, resultant hardware modifications, test procedure changes, new test equipments, and provisioning and documentation changes.

The primary problems foreseen were the ability to translate the supervisory baseband above the digital baseband and concurrently contain the emission spectrum to 14 MHz.

Additionally, some problems were encountered in the use of various types of combiners due to their functional design and switching speeds.

The Digital Transmission Application Project

The results of the previous tests determined that commercially available hardware could be modified to support the interim digital requirements of the U.S. Military. Up to this period of time, however, no system's testing had been performed.

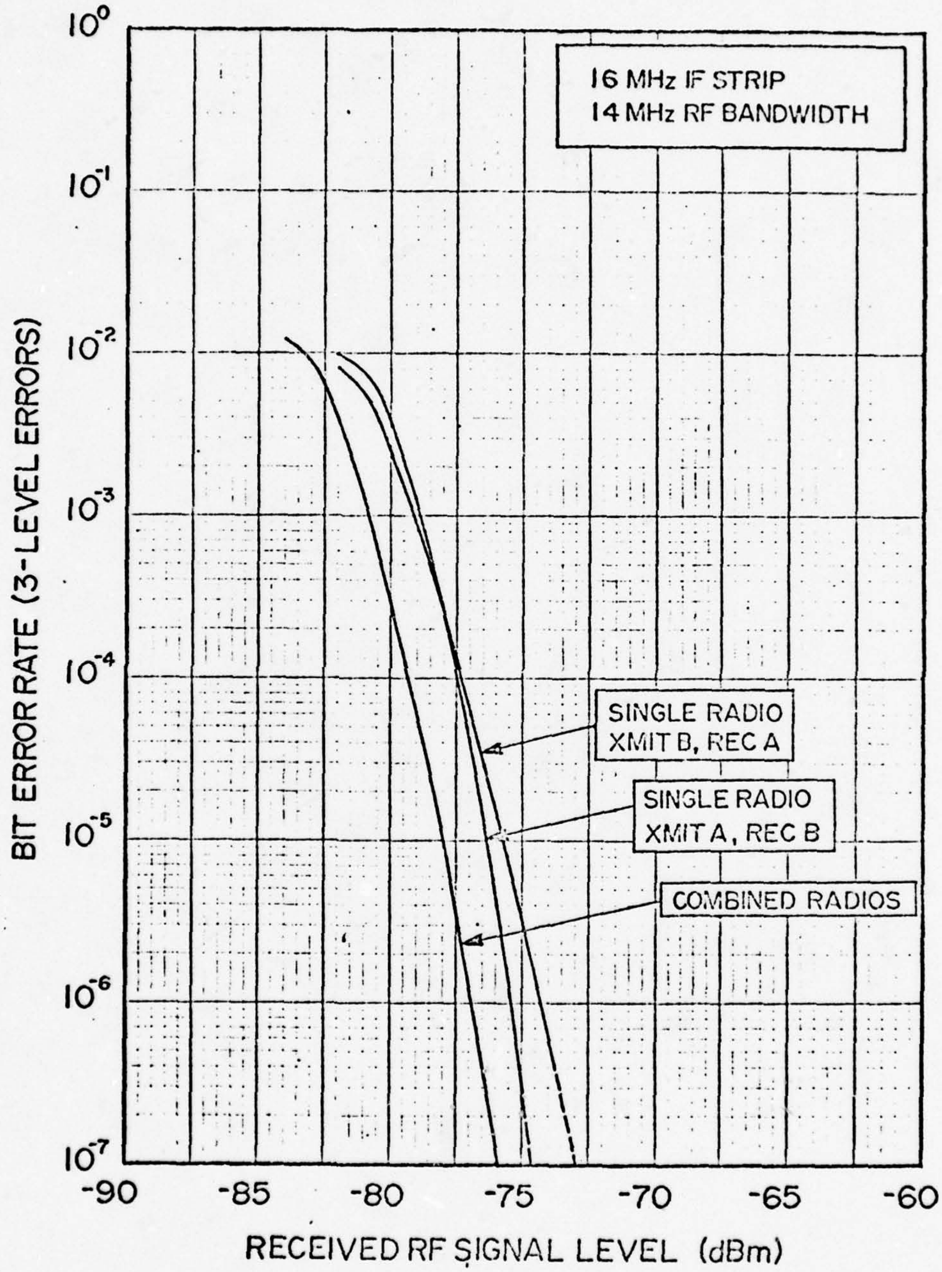


Figure 6-9. BER vs RSL.

(Source: Richard E. Skerjanec, Test Results For Digital Testing Of The Candidate Radios For The DCS Microwave Radio, OT TM 73-137C, Institute of Telecommunications Sciences, April 1973, p. 14.)

With respect to this, the DCA elected to institute a pilot digital system within the DCS and issued guidance to the Department of the Army with the DCA Management/Engineering Plan (MEP) dated 21 April 1972.

The Department of The Army, on 27 January 1972, in response to DCA direction, requested that the U.S. Army Strategic Communications Command prepare plans covering the installation of a test configuration for system integration and familiarization testing at Fort Huachuca, Arizona and operational testing of the PCM/TDM equipments used in European upgrades.[16]

The USASTRATCOM, in May 1972 issued the Concept Plan for the PCM/TDM Digital Transmission Application Project (DTAP) Engineering and Operational Testing. In doing so, many army commands and agencies became participants in the project. They included the USASTRATCOM, the US Army Communications Electronics Engineering Installation Agency (USACEEIA), the USASTRATCOM-Europe, the US Army Test and Evaluation Command (USATECOM), the US Army Electronics Proving Ground (USAEPG), the US Army Electronics Command (USAECOM), the National Security Agency (NSA) and other subordinate elements determined by their respective organizations.

The objectives of the project were to develop and prove operational maintenance and logistics procedures for a fully operational, secure, PCM/TDM communication system. Furthermore, the project was to permit testing and evaluation of the PCM/TDM equipments, procedures and personnel under actual field conditions for the first time. Results of

the tests were to be used in establishing standards upon which future systems concepts, implementation and operations could be based.[17]

The system configuration tested at Fort Huachuca, Arizona was designed to simulate some of the conditions anticipated in the DCS Frankfurt-Koenigstuhl-Vaihingen (FKV) Transmission Subsystem Upgrade. The proposed DTAP site locations are shown in Figure 6-10.

The equipment tested under the DTAP included the NSA modified TSEC/CY-104, the VICOM 8 port Digital Multiplex (TDM), the WB-1 wideband modem, and the Motorola MR 300 (AN/FRC-80)(v)) and the DCS Microwave Radio when it became available.

The evaluation objectives[20] of the Fort Huachuca tests were to investigate the interference of PCM/TDM and FDM systems with respect to parallel paths, co-location, frequency assignments, and polarization (this problem had been identified in the FCC docket of Inquiry No. 19311 but had not been answered when the DTAP began), along with the interface of FDM derived and TDM derived voice channels. Also, of major importance was the maximum channel loading of TDM systems, spectrum signatures, and propagation characteristics. Each of these things impacted on the spectrum considerations that had come under national and international regulatory scrutiny. Equipment and system reliability, maintenance procedures, level of personnel training, human factors engineering, and operational procedures were also to be evaluated.

The DTAP Test Facility was established in July 1972. Equipment procurement delays negated installation of the PCM/TDM equipments until

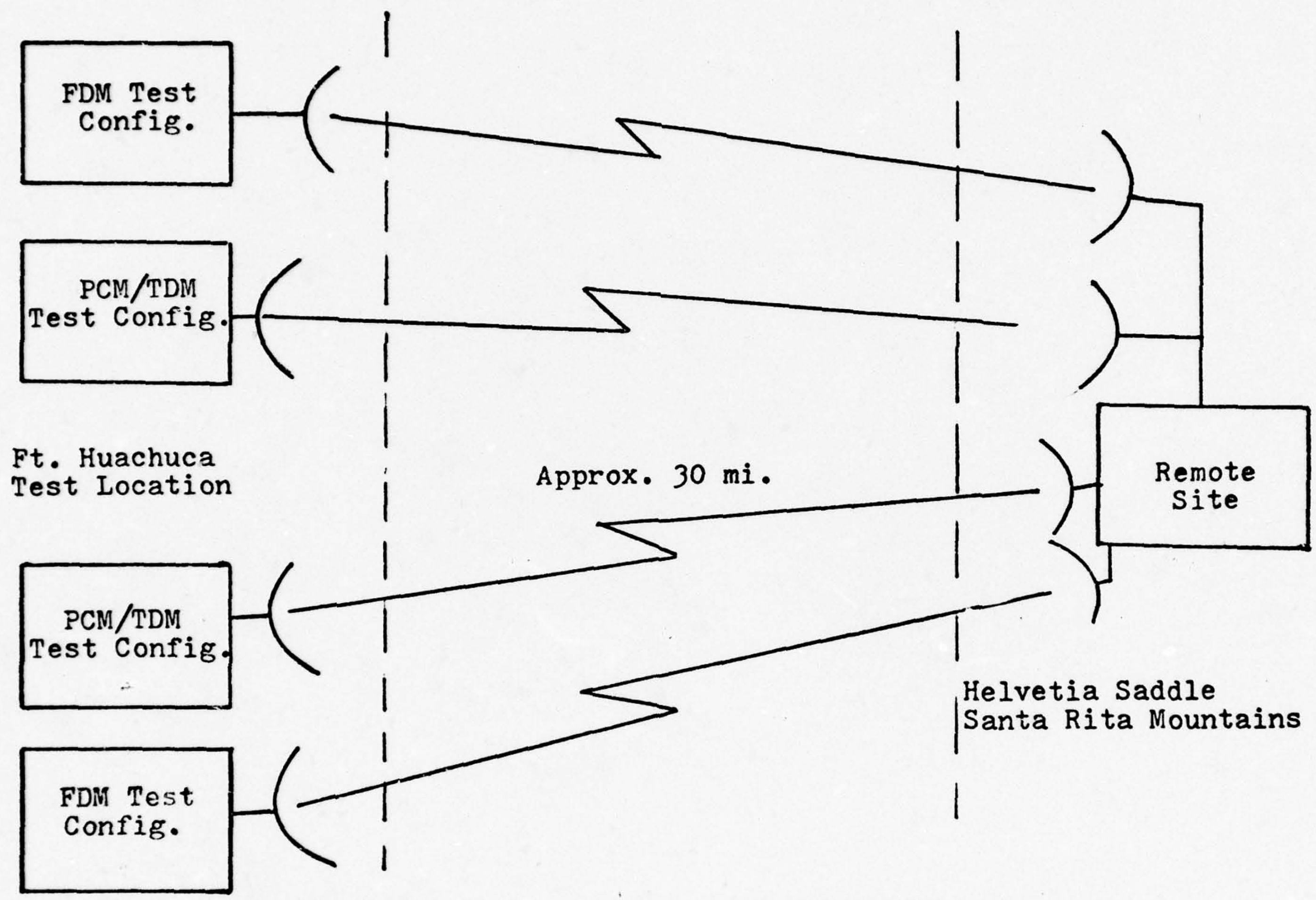


Figure 6-10. Proposed DTAP Test Site Locations.

1 February 1973. The microwave equipment was installed immediately thereafter in a back to back configuration, simulating a 30 mile, LOS microwave radio link with provisions to independently vary the received signal level in both directions.

The tests performed, although viewed as unsuccessful, proved to be beneficial in providing the insight of what mistakes to avoid in the future. A review and analysis of the data led to such determinations as: an inadequate grounding system throughout the test bed, the need for automated data reduction, discrepancies in baseline data for both multiplex and microwave, different modification levels for supposedly the same identical equipments (reflecting a lack of production control of the equipments), manual discrepancies, and a strong need for systems engineering guidance.

These problems along with equipment failures, (as expected in stringent testing), and other internal problems allowed DTAP to be overtaken by time and much of the intended purpose was negated. As a consequence, the entire program was held in abeyance with a skeleton test team for a period of four months. The program objectives were realigned in keeping with realizable objectives, keyed to a time phased procurement and implementation plan reflecting DCS and MILDEP upgrades and new systems implementations. The realigned program was renamed, "Digital Transmission Evaluation Project (DTEP)."

The Digital Transmission Evaluation Program

The Digital Transmission Evaluation Program (DTEP) is an engineering evaluation project which was established by the U.S. Army Communications Command (USACC), at Fort Huachuca Arizona, in August 1973, in support of the Defense Communications Agency (DCA).

The purpose[21] of the DTEP is to evaluate selected commercially developed equipment that may have a direct application potential within a digital Defense Communication System (DCS). Information garnered from this test effort was, and is, needed to develop and maintain an adequate technical base to enable the DCA and the MILDEPS to plan and program effectively for the modernization of the DCS.

Testing doctrine for the DTEP was developed after having drawn on the experience of the other test beds discussed previously, and on the expertise of the U.S. Army Communications-Electronics Engineering Installation Agency (USACEEIA), the U.S. Army Electronics Command (USAECOM), the Office of Telecommunications/Institute for Telecommunications Sciences, and the commercial companies which had recently purchased or who operate, 10-40 Mbps digital transmission systems.

Equipments were selected[22] using the guidelines of the Defense Communications Circular 330-195-2, titled "Tests and Evaluation: Evaluation of Selected Commercially Developed Equipment and Software," and included that equipment which was already installed, or had been made available under the DTAP. This included the Raytheon RDS-80 and RDS-80 G digital microwave radios, the Raytheon RDM-425 PCM/TDM

multiplex, the modified Collins MW-518 QPSK microwave radio, the Avantek DR8A microwave radio, the DCS Microwave Radio as a result of the TPVM testing, and the TD-968 digital multiplexer that was being built by Martin Marietta.

The tests which were to be performed on the selected digital equipments were, for the most part, taken from the original DTAP plan.

The approach to the task was to perform back-to-back tests to establish a valid data base and to validate the operational performance of the equipment against the manufacturer's performance specifications. This was to be accomplished first, on the individual equipments, and then, with the equipments configured to operate as a system over a simulated LOS microwave path. Once the data base had been established with confidence, the next step was to perform the same tests over an actual microwave link.

The measurement objectives[23] are:

1. Determine interface parameters between radio, TDM/PCM, etc.
   a. Levels and tolerance limits
   b. Amplitude response and limits
   c. Phase response and limits
   d. Interface timing tolerance
2. Determine transfer parameters
   a. Voice channel transfer performance parameters
   b. Data modem transfer performance parameters

c. Clock transfer performance parameters

d. Subsystem interrelation of clock parameters

e. Redundancy and protection techniques

f. Bit error rate as a function of various interface parameters

g. Spectrum control filtering effects on performance

h. Error multiplication through encryption, multiplexing and encoding in multi-link systems

i. Radiated spectrum efficiency

j. Integration of supervisory/service channel into multiplex plan.

3. Determine path influence on transfer parameters

a. Multi-link regeneration requirements

b. System timing, transfer and synchronization

c. Interference susceptibility

d. Path depolarization effects

The reader can see that the magnitude of the work to be accomplished in the DTEP was very large. This reflects the ambitious effort the Military made to acquire a knowledge of the digital techniques and their application to digital transmission systems.

As in the case in most test efforts of this nature, a technical assessment of the test objectives and the experience gained through actual testing permitted the DTEP measurement objectives to be realized by performing fewer tests as depicted in Table 6-1.

Table 6-1

DTEP TEST MATRIX

		RDS-80G	RDS-80	MW-518	FRC 162	DR8A
BER vs RSL	*	X	X	X	X	X
Link Characteristics		X				
Link BER Avail.	*	X	X	X	X	X
C/I	*	X	X	X	X	X
Spectrum Eval.	*	X	X	X	X	X
Data Rate Eval.		X		X		
Freq. Accuracy & Eval.		X		X		
T1 BER vs RSL		X	X	X		
Switch Errors		X			X	X
Cross Polarization Tests		X	X			
Pulse Jitter		X				
Interface BTWN MUX		X				
Mean Time to Acquire Frame		X	X			
Multiple Hop Transmission			X			
Quantizing Distortion				XX		
Voice Chan. Cross Talk				X		
O/W S/N				X		
Repeater w/o Regen.					X	
Output Power						X

The best comparison of the digital systems was accomplished by the performance of four basic tests:

1. Bit Error Rate (BER) vs Received Signal Level (RSL)
2. Carrier to Interference Ratio (C/I)
3. Emitted Power Spectrum
4. Special Tests

DTEP Testing

The intent here is not to show how one microwave radio compared with the others, but rather to highlight some of the significant factors that evolved as a result of the tests. The complete details of the tests on the individual equipments and their system configurations are contained in the final DTEP reports for the respective equipments.

Bit Error Rate and Received Signal Level

This basic test yields important information for use in evaluating digital equipment and digital systems. The combined effects of thermal noise, intersymbol interference and bandwidth are included in this measurement. The overall performance of the system is analyzed by comparing data derived from this test and comparing it to theoretical predictions.

This is an adequate procedure when comparing systems with the same bandwidths, bit rates and modulation techniques. When any one of these factors is allowed to vary, the RSL is no longer a common denominator and a new basis for comparison e.g. the energy-per-bit (E_b) versus noise power density (N_o) ratio (E_b/N_o) must be used. The following relationship[24] is used to equate RSL to E_b/N_o.

$$E_b/N_o = (\mathrm{RSL})\mathrm{dBm} - (10 \log_{10} R + 10 \log_{10} kT + 30 + \mathrm{NF})\mathrm{dBm}$$

where: RSL = received signal level in dBm

R = bit rate in bits per second

$k = 1.38 \times 10^{-23}$ joules per ^{o}Kelvin

$T = 290^{o}$ Kelvin

30 = conversion factor from dBW to dBm

NF = noise figure in dB .

Figure 6-11 depicts a typical setup used to perform BER vs RSL tests. The attenuators are used to simulate path losses. Typical BER curves are presented in Figure 6-12 as well as in Chapter Three (Digital Modulation Techniques).

Heavy filtering (14 MHz filter and a 19.804 Mbps data rate) was applied to the Collins MW-518 microwave radio[25] to increase the spectral efficiency of the radio to a value greater than 1-Bit/Hz. During the performance of the BER vs RSL it became evident that a higher E_b/N_o was required for a given BER (2dB higher at 1×10^{-7} BER) and as the E_b/N_o increased, the BER curves diverged approximately 5dB from theoretical (see Figure 6-13). This was attributed to intersymbol interference, which was in effect, masked by the thermal noise at the threshold region, but became more predominant at the higher RSL's.

Degradation due to saturation[26] was demonstrated during the performance of the BER vs RSL test on the Raytheon RDS-80. Degradation occurred when the RSL was made higher than -30 dbm and is shown in Figure 6-14. The problem was attributed to the AGC circuit and was corrected on the RDS-80G version of this radio.

Carrier to Interference Ratio (C/I)

An important consideration from the standpoint of Electromagnetic Compatibility (EMC), Electromagnetic Interference (EMI) and jamming is the carrier to interference (C/I) ratio. Swept Frequency (CW) and

BEST AVAILABLE COPY

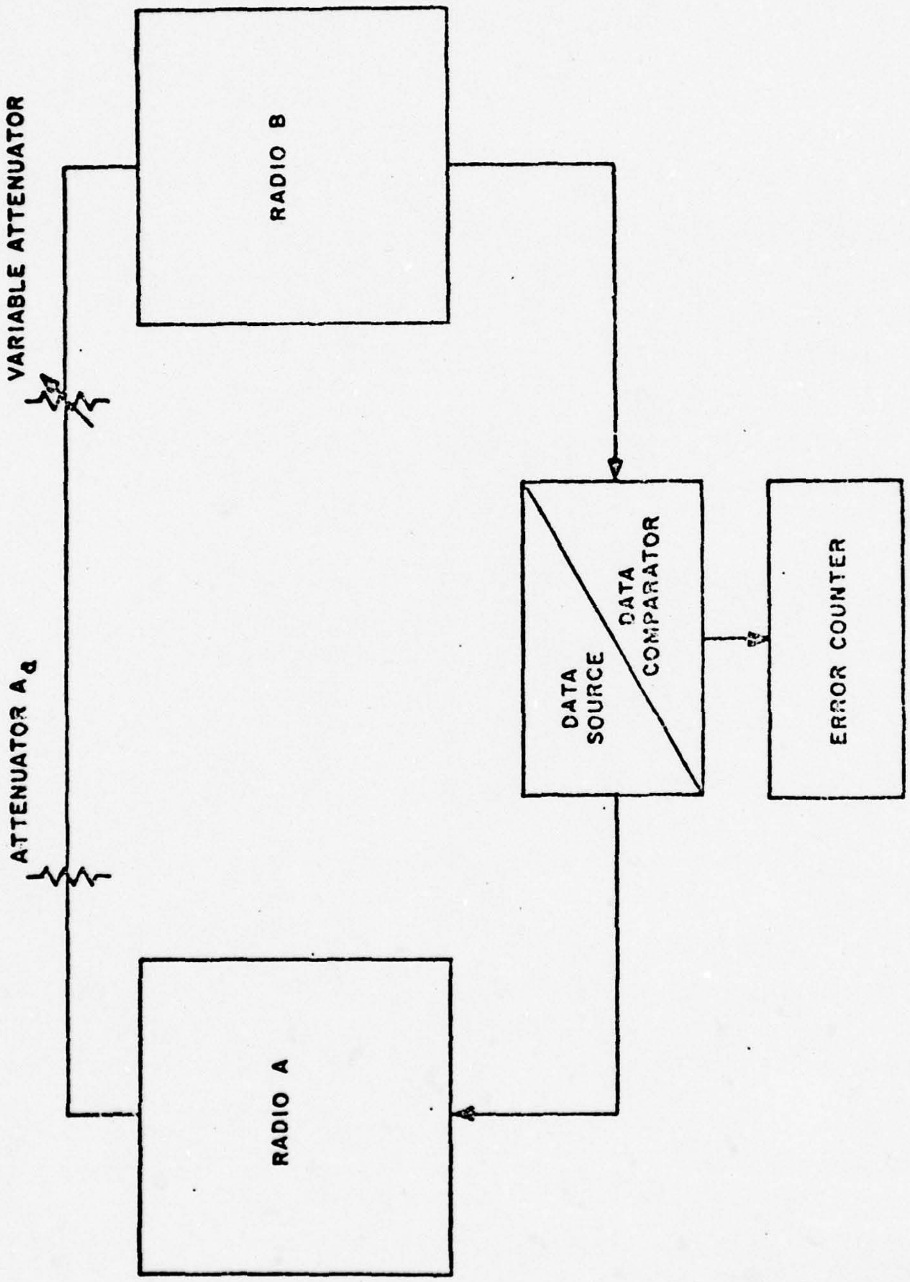


Figure 6-11. Typical BER vs RSL Test Configuration

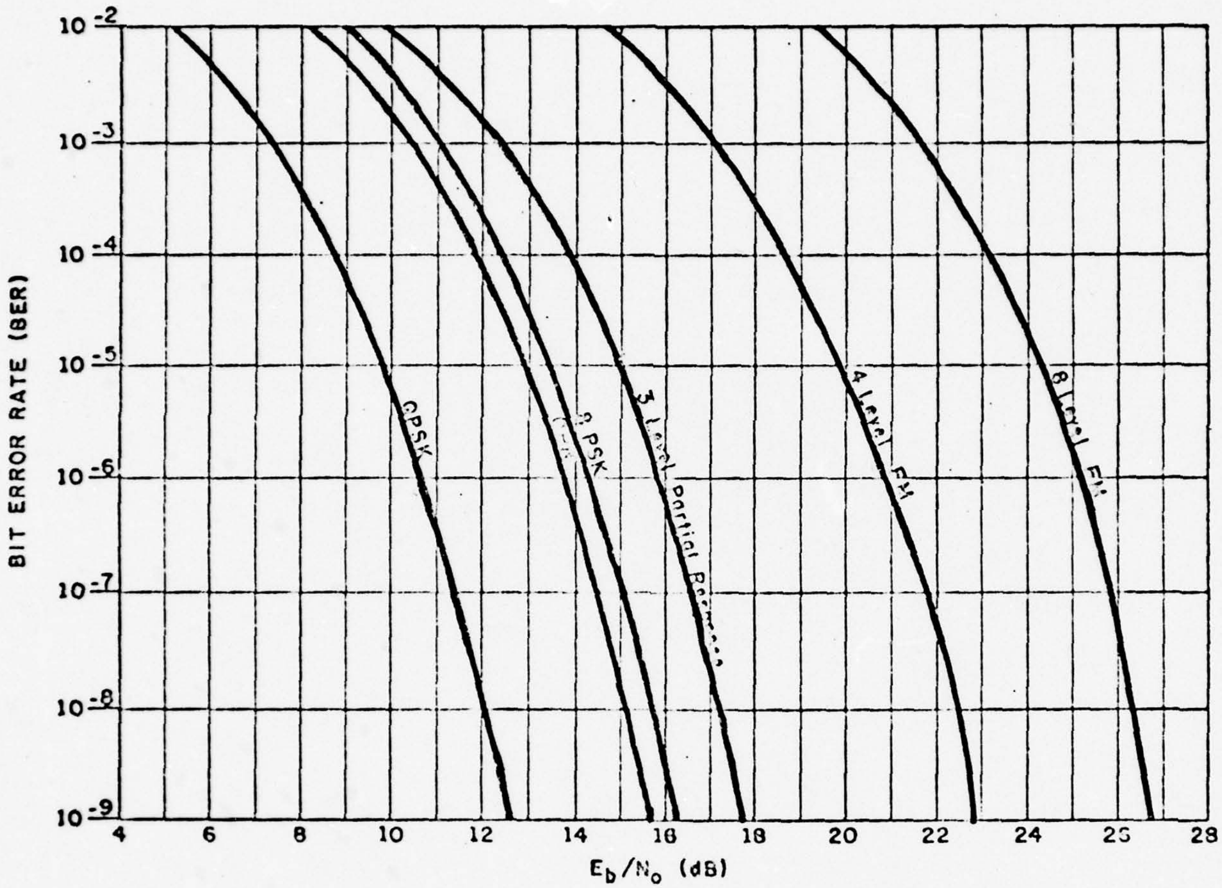


Figure 6-12. Bit Error Rate Summary (Theoretical)

Source: Digital Transmission Evaluation Project Equipment Comparison CCC-SR-75-DTEP-007. p. 27, Figure 14.

BEST AVAILABLE COPY

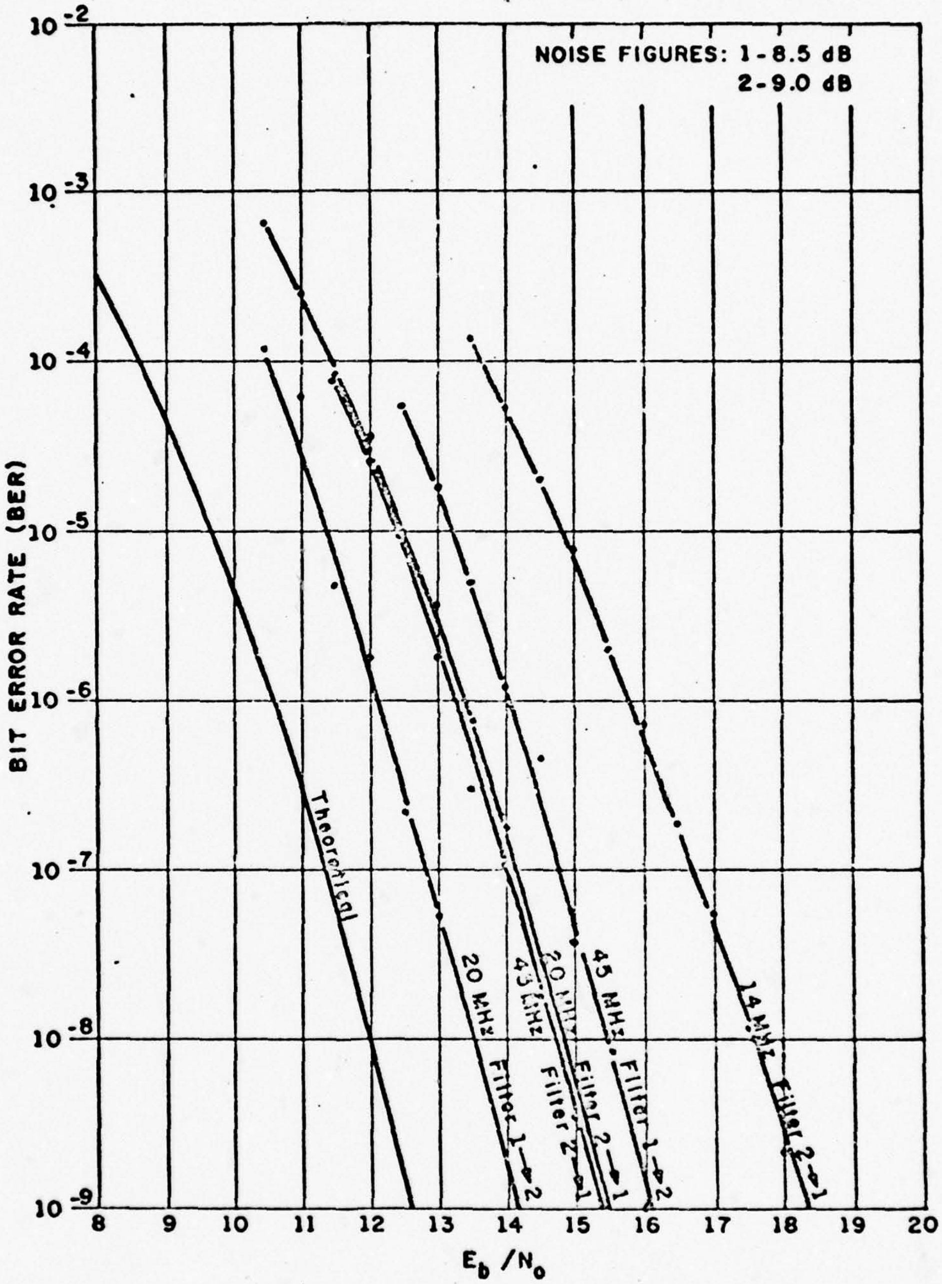


Figure 6-13. BER vs RSL (R=19.804 Mbps)

Source: Digital Transmission Evaluation Project MW-518 (QPSK) Test Final Report CCC-CED-75-DTEP-008, p. 13, Figure 6.

BEST AVAILABLE COPY

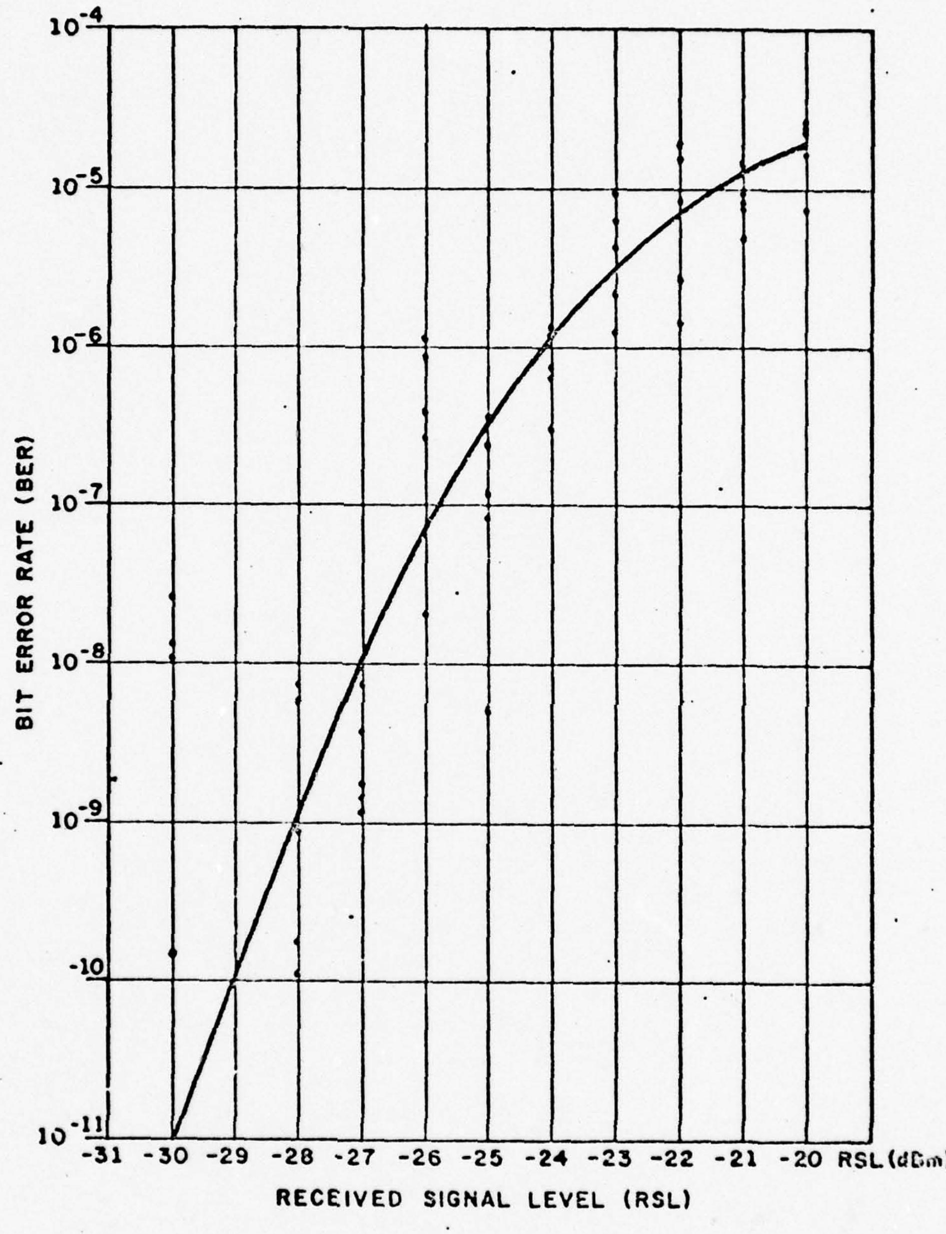


Figure 6-14. Bit Error Rate vs Receive Signal Level
(Saturation Region)

Source: Digital Transmission Evaluation Project RDS-80 Test Final Report p. 13, figure 6.

co-channel (modulated interferer) interference effects on the different digital microwave radios were evaluated using a test configuration similar to that shown in Figure 6-15.

The greatest effects of the swept frequency interference[27] occurred when the interfering signal (f_I) fell at the first null and not at the center frequency (f_o). This was demonstrated during the AN/FRC-162 3-level Partial Response microwave radio C/I testing. The bit error performance is depicted in Figure 6-16 for C/I = 15 dB, f_o = 8390 MHz, and for RSL values of -70 dBm, -73 dBm and -76 dBm.

Carrier to Interference tests[28] that were conducted on the Raytheon RDS-80G microwave radio show the effects on BER for co-channel interference levels of 12, 15, 18, 21, and 24 dB as well as the no interference case. These are presented in Figure 6-17.

Co-channel interference on the AVANTEK DR8A[29] is shown in Figure 6-18. The increased susceptibility of QPR modulation used in the DR8A microwave radio as compared to the QPSK modulation of the RDS-80 microwave radio is demonstrated by comparing Figures 6-17 and 6-18. Higher RSL's for operation in the DR8A QPR system which is subject to interference indefinitely do not improve the BER of the system, but instead "plateaus" in the BER vs RSL curves occur as shown in Figure 6-19.

An independent study[30] performed by the Office of Telecommunications Sciences with the AN/FRC-80 (v)3 microwave radio, under the sponsorship of the DTEP, showed that FDM-FM systems were more susceptible to

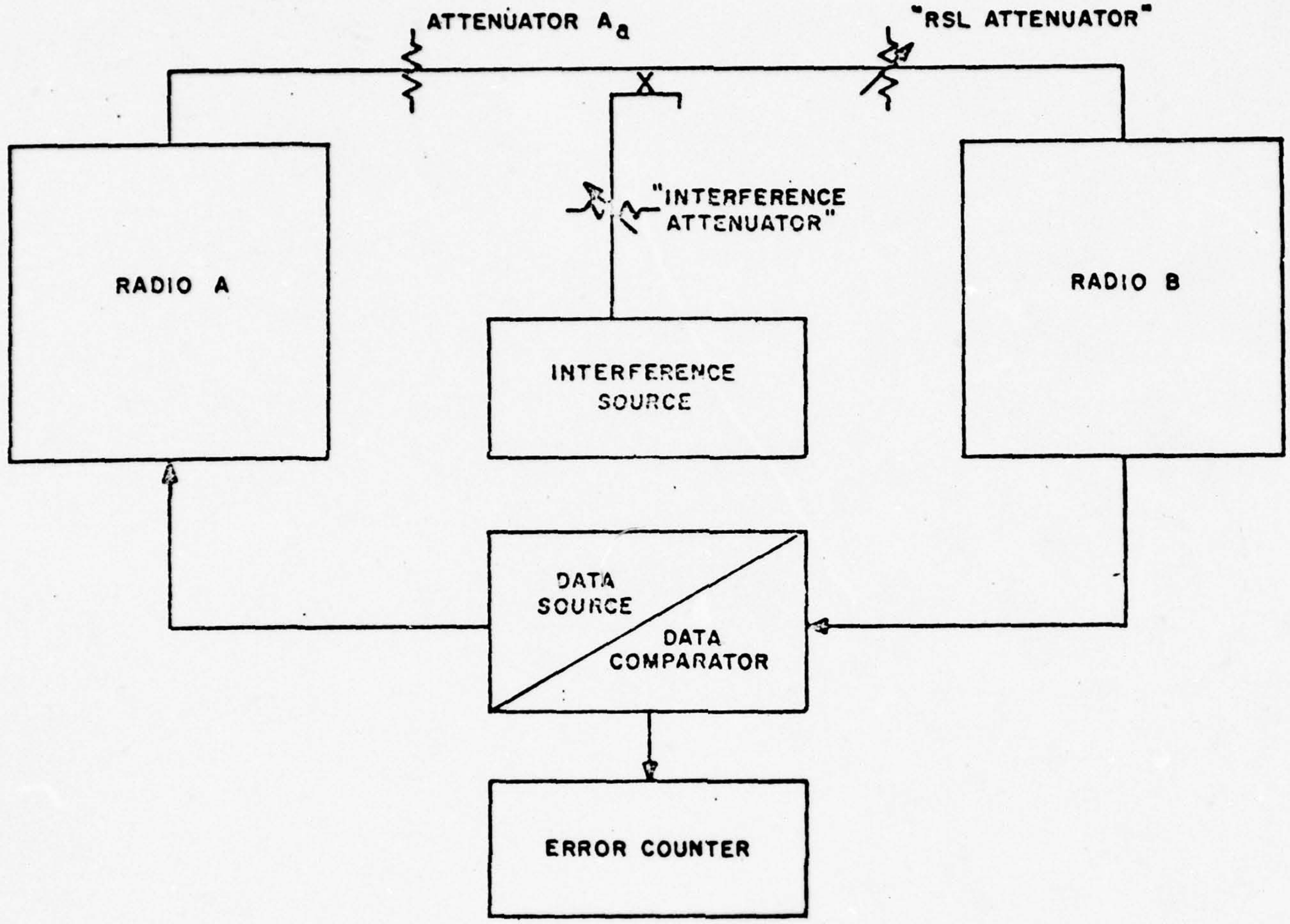


Figure 6-15. Typical C/I Test Configuration

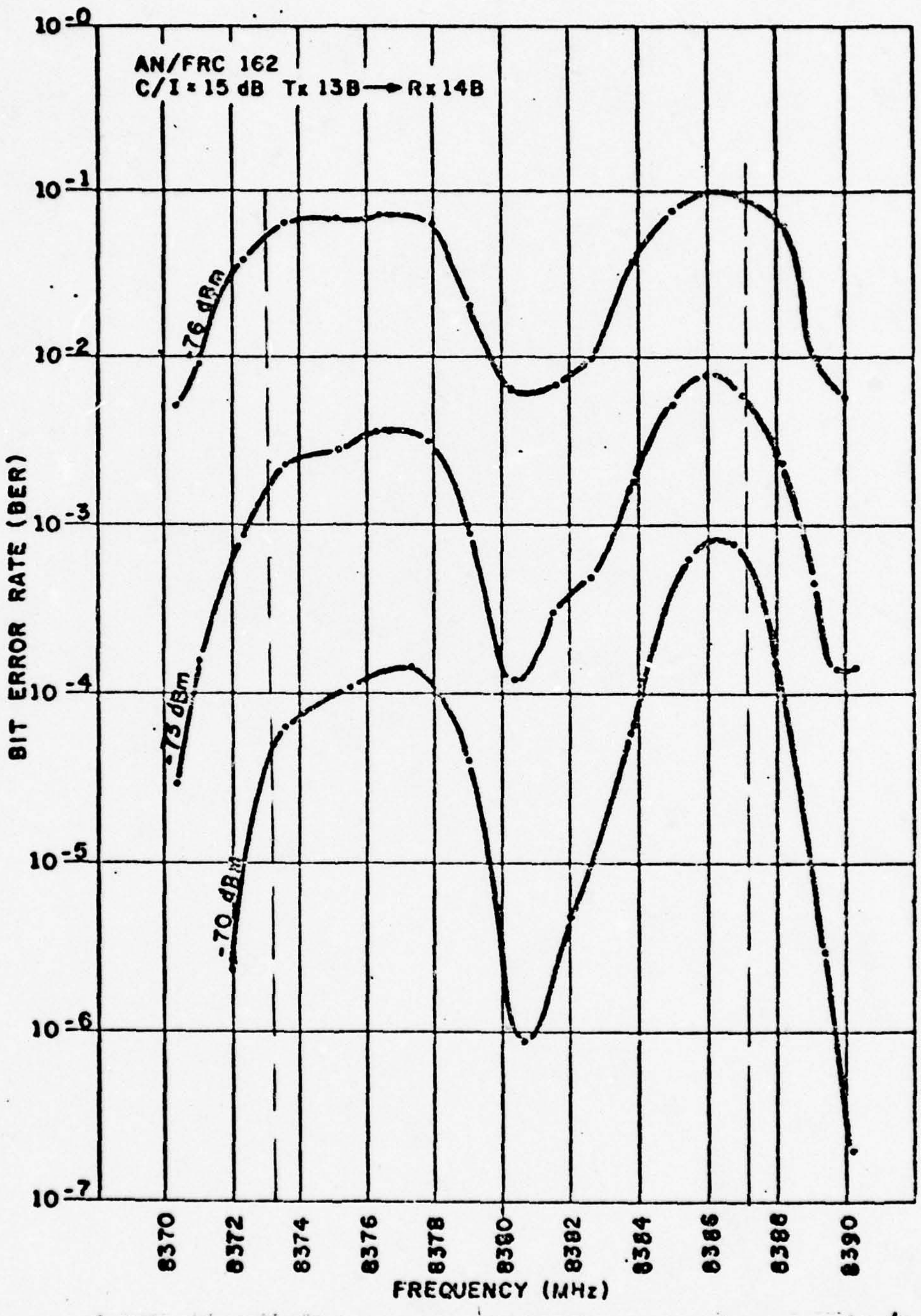


Figure 6-16. Swept Frequency Interference Curves (C/I=15 dB)

Source: Digital Transmission Evaluation Project AN/FRC 162 Test Final Report, p. 23, figure 14.

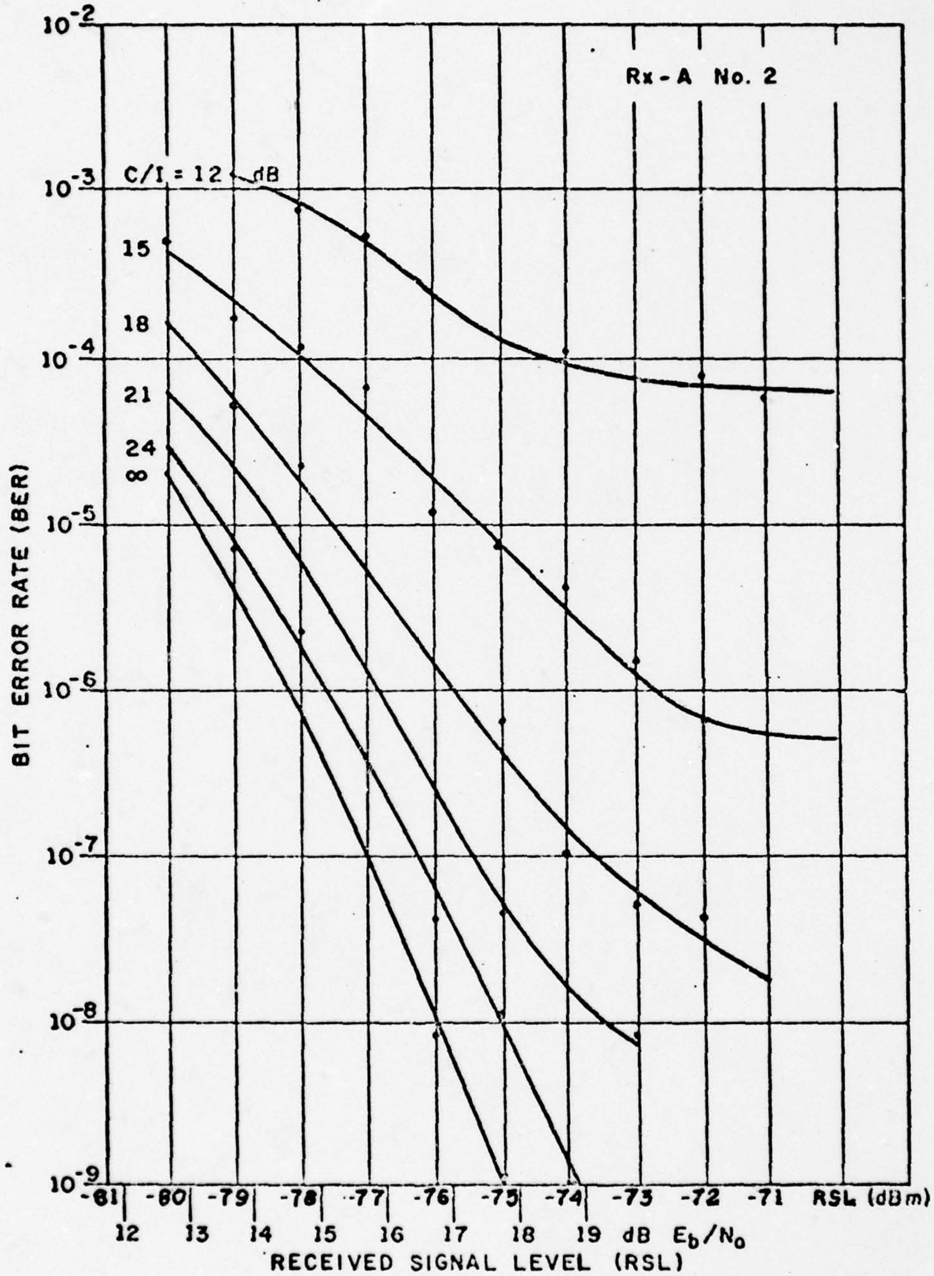


Figure 6-17. Co-channel Interference (FDM on QPSK)

Source: Digital Transmission Evaluation Project RDS-80 G (QPSK) Test Final Report, p. 21, Figure 9.

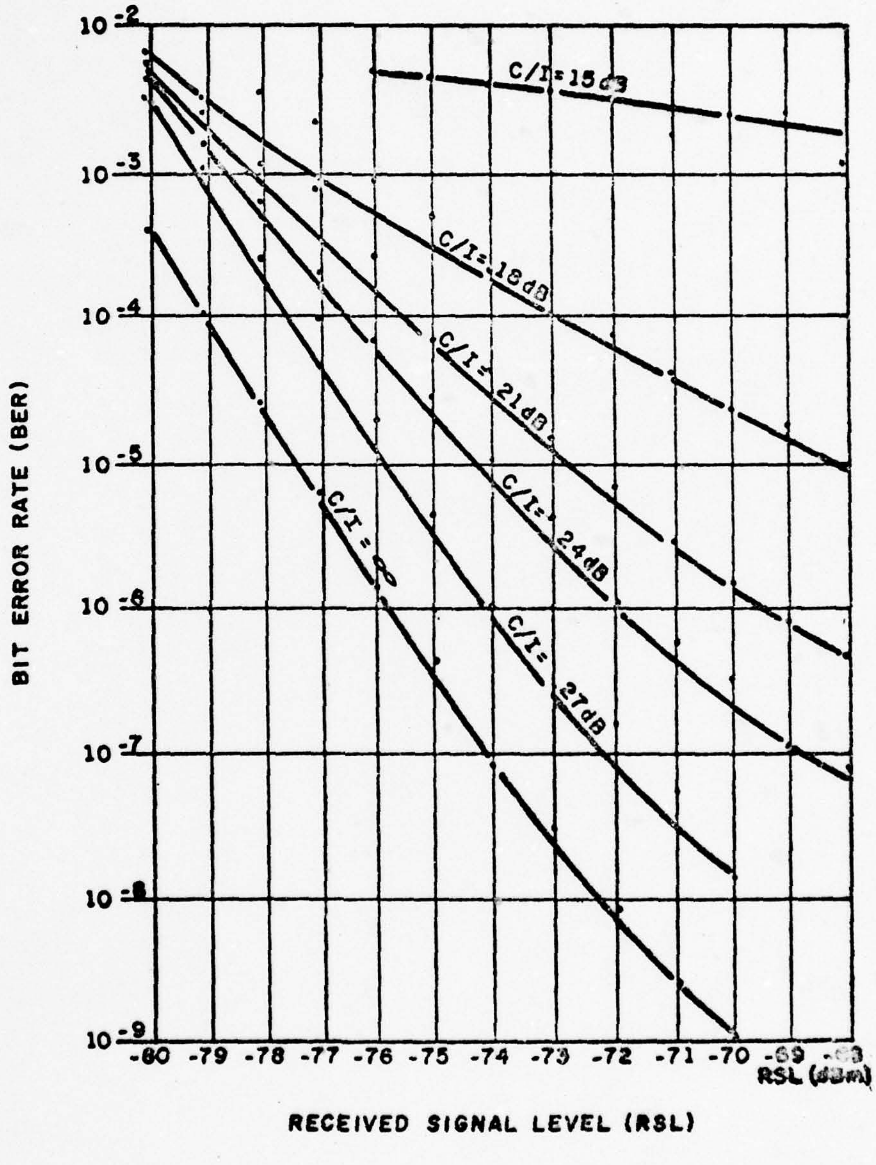


Figure 6-18. Co-channel Interference (FDM on QPR)

Source: Digital Transmission Evaluation Project DR8-A Test Final Report, p. 16, Figure 7.

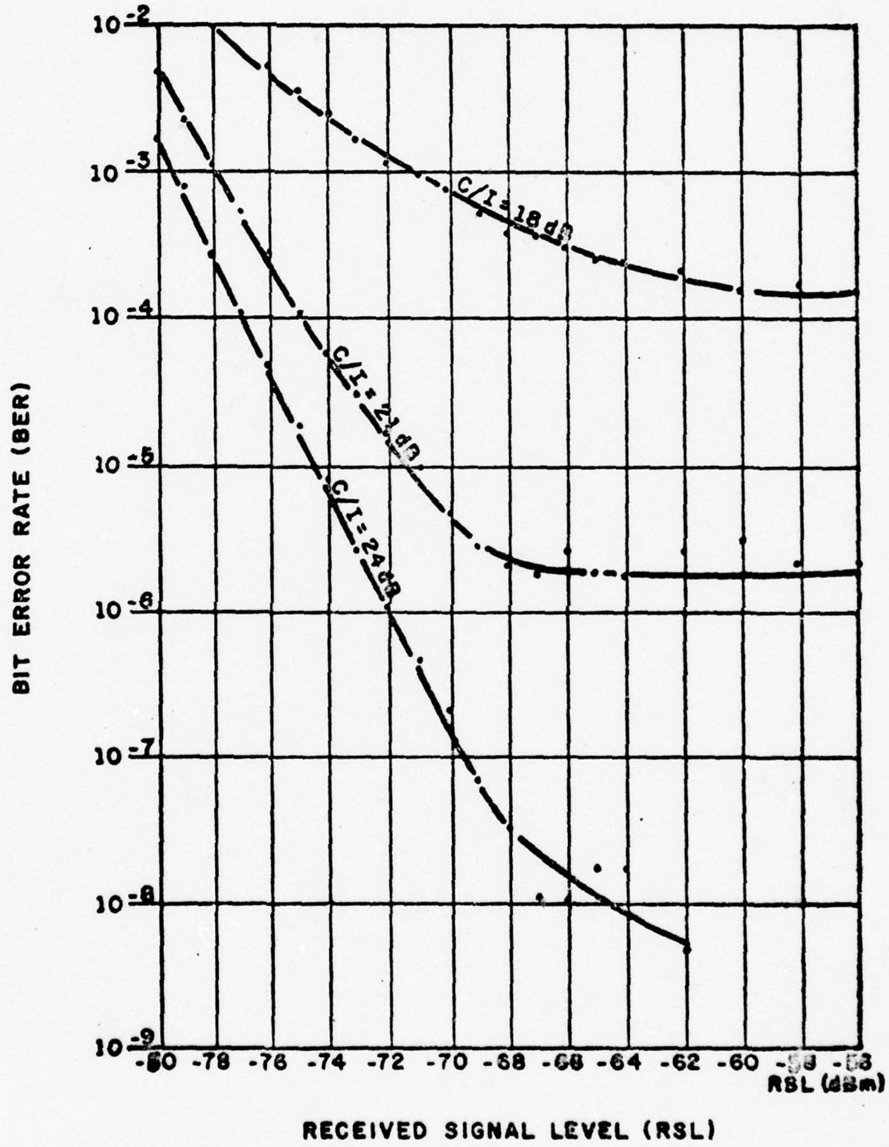


Figure 6-19. C/I At Higher RSL's

Source: Digital Transmission Evaluation Project DR8-A Test Final Report, p. 19, Figure 10.

TDM-FM interference than vice-versa. They also determined that (1) for co-channel interference, a C/I ratio of even 65 dB begins to degrade the system NPR, (2) at the half channel or first null C/I ratio of 54 dB starts to degrade the system NPR and (3) a C/I ratio of 34 dB, at the second null has the same effect.

Emitted Power Spectrum Evaluation

Results of the Richards-Gebaur tests established that the emitted spectrum of the 3-level partial response system must be studied with the presence of the orderwire subcarrier. It was not known what the orderwire subcarrier frequency should be and what effect it would have on the digital baseband and vice versa.

It was also necessary to determine if the selected DTEP microwave radios would meet the requirements of FCC Docket 19311.

The question concerning the orderwire was answered through an evaluation performed by the Office of Telecommunications Sciences[31] under the sponsorship of the DTEP. It was through the efforts of this evaluation[32] that a determination was made to use a 7 MHz peak to peak baseband deviation and a 7.5 MHz subcarrier with a 1.5 MHz deviation for the best overall performance. This is summarized in Figures 6-20 and 6-21.

The tests performed at the Fort Huachuca Arizona test facility[33] used the typical power test configuration shown in Figure 6-22. The significant findings of the evaluations were (1) that heavy RF filtering was

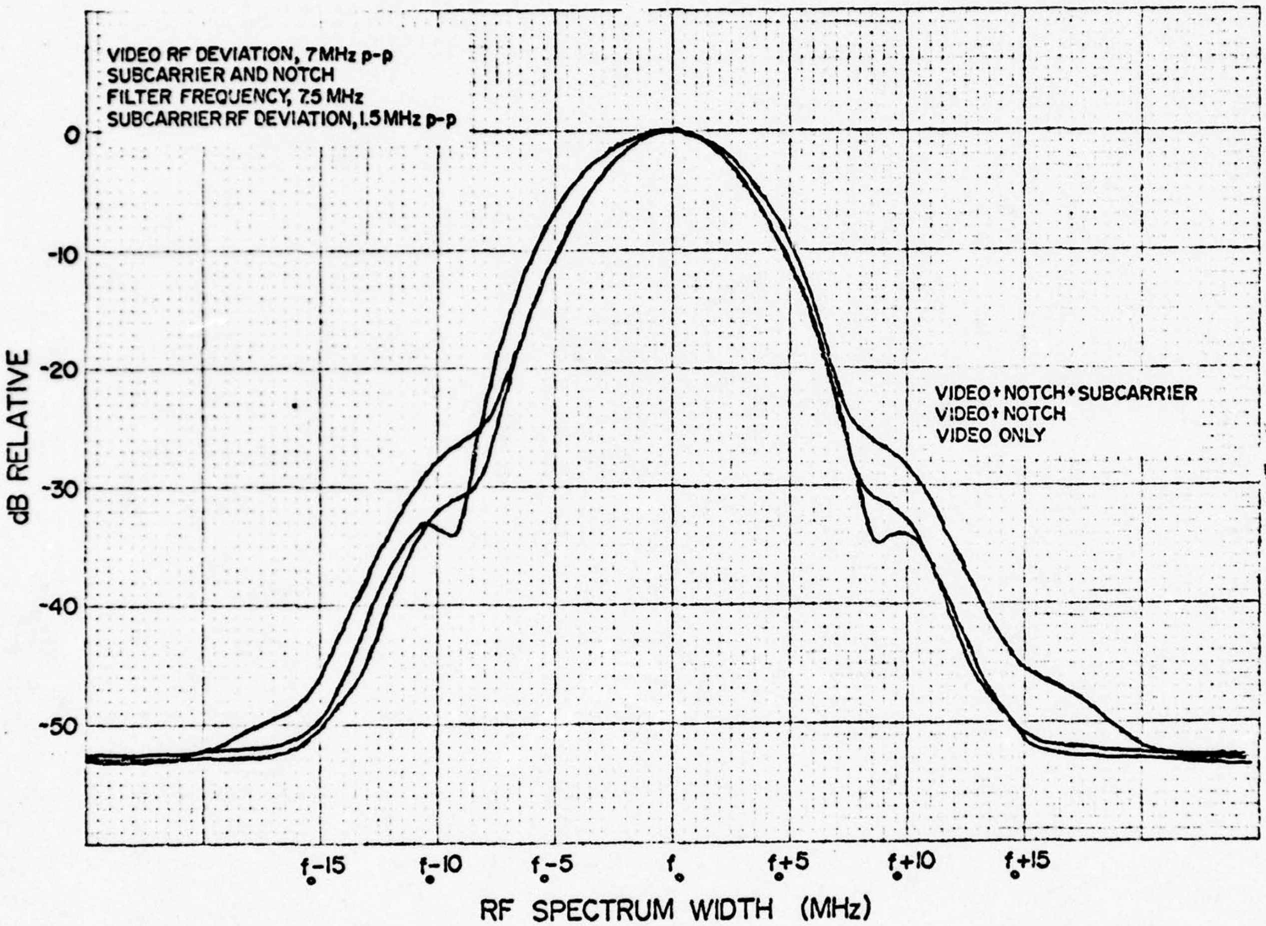


Figure 6-20. Emitted Spectrum Amplitude and Baseband Deviation

Source: AN/FRC-80(v)3 Retune and Time Division Multiplex Interface Investigation. p. 70, figure 4.23.

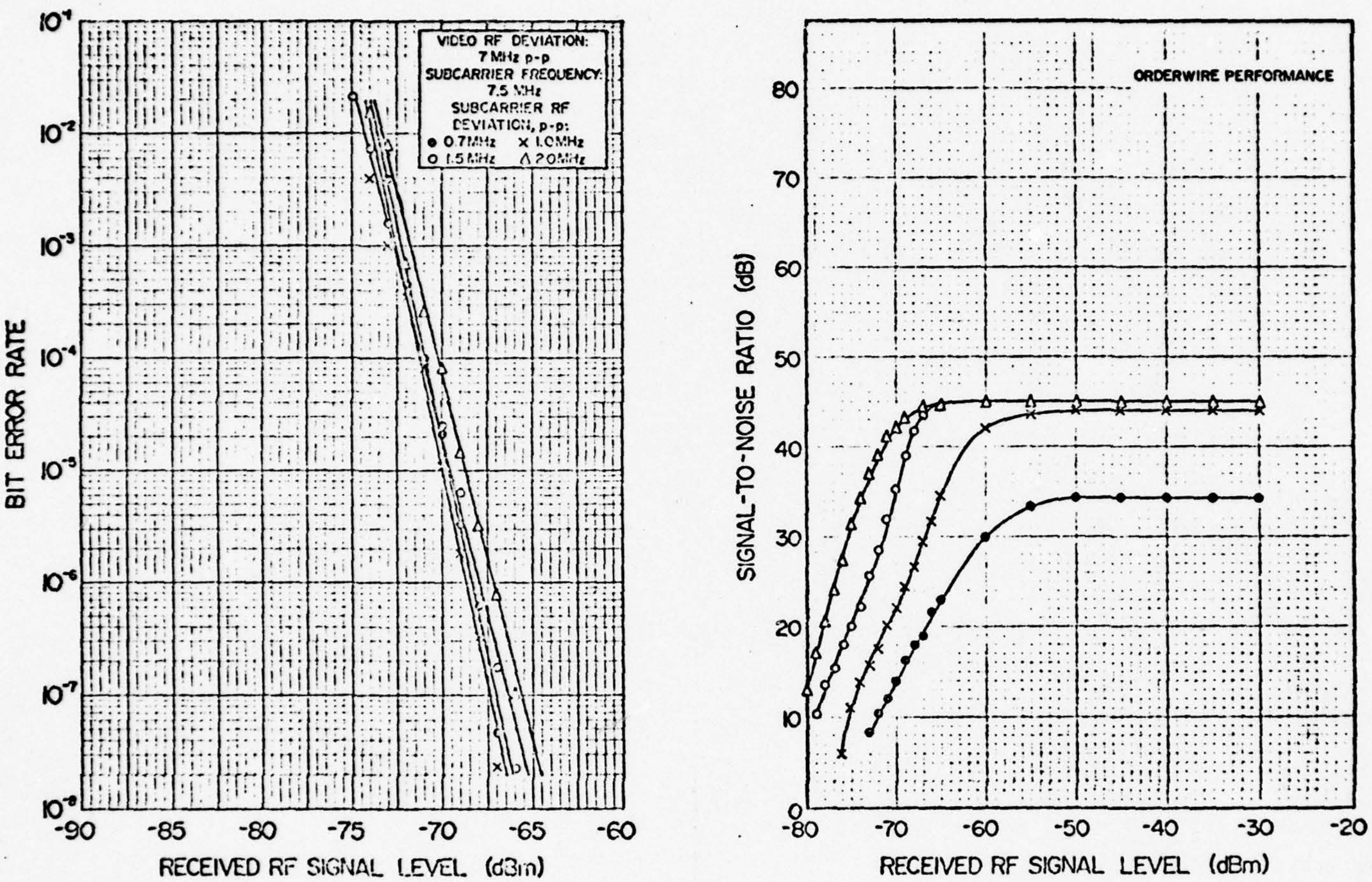


Figure 6-21. Orderwire Performance.

Source: AN/FRC-80(v)3 Retune and Time Division Multiplex Interface Investigation. p. 78, figure 4.30.

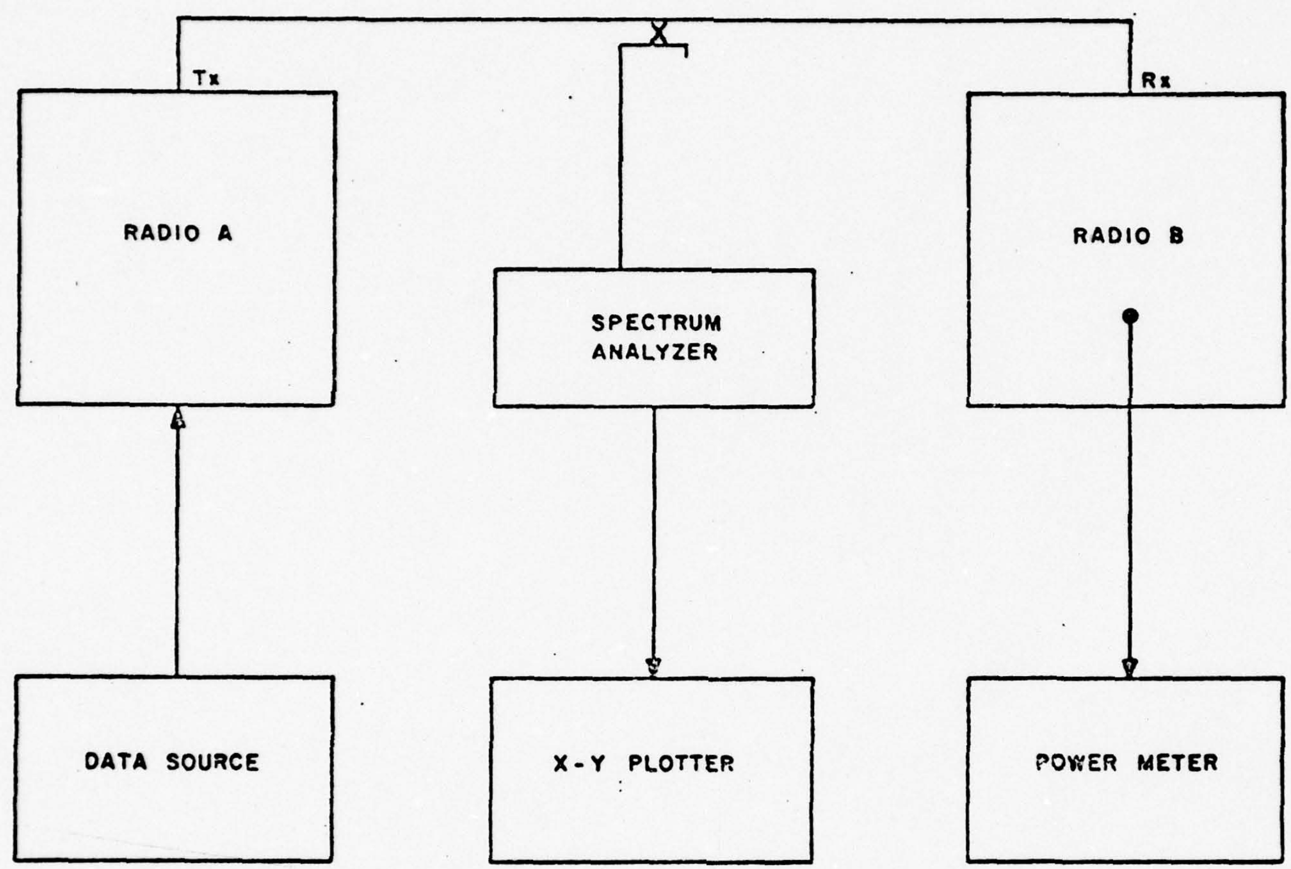


Figure 6-22. Typical Power Spectrum Test Configuration

required to make the systems comply with the FCC 99% power bandwidth requirement and (2) that none of the radios met the side lobe attenuation required by the FCC mask. Figures 6-23 and 6-24 typify the results of this evaluation on the QPSK systems.

Special Tests

Bit error rate and errors were the subject of four evaluations performed in the DTEP. The evaluations related traveling wave tube (TWT) output power to BER, diversity switching and errors, link availability with respect to BER and the effects of baseband repeaters on BER.

Traveling wave tubes (TWT) are constrained to work in a linear region of their characteristic curves. The TWT is capable of more power out than what it is rated for in linear operation. The effect of driving the output power[34] of the TWT beyond its usable rating is shown in Figure 6-25.

Errors incurred during diversity switching were studied during the AN/FRC-162 microwave radio test. It became evident that switching techniques[35] and switching levels that were used for FDM-FM systems would not be acceptable for digital transmission systems. Error counts ranged from 2 to 382 for each test period when fast fades were simulated with waveguide attenuators as shown in Figure 6-26, Switching Test Configuration. Although the switching caused an average of 100 errors for each switching event, which met the published performance specifications, it was desirable to have a more consistent performance. The switch was redesigned[36] so that no switching takes place above -66 dBm. Once the

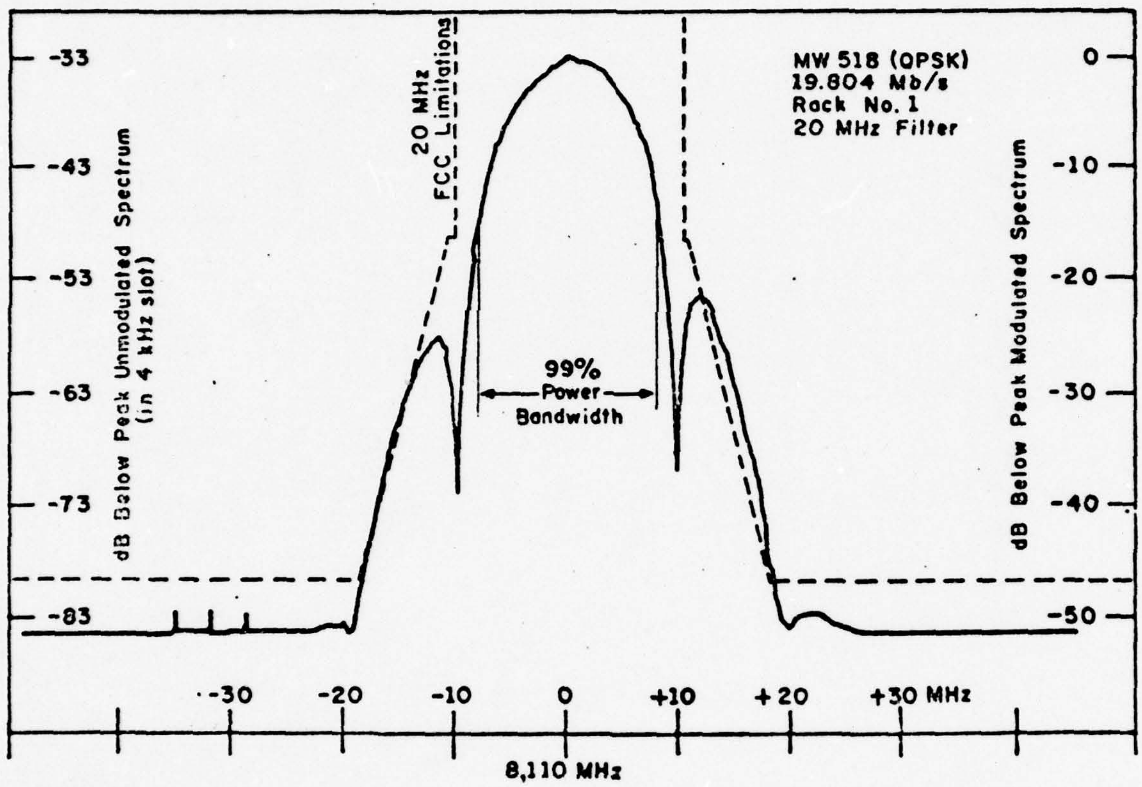


Figure 6-23. Power Spectrum With FCC Mask MW-518 (QPSK)

Source: Digital Transmission Evaluation Project Equipment Comparison, p. 63, figure 44.

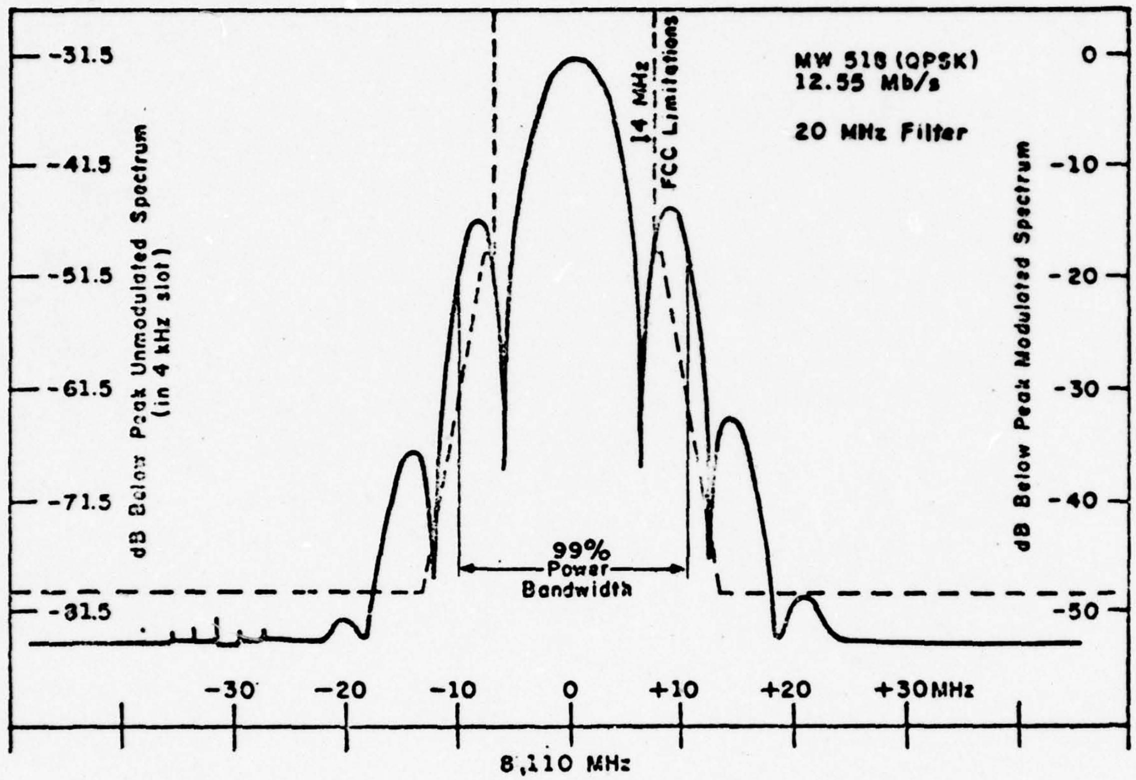


Figure 6-24. Power Spectrum With FCC Mask

Source: Digital Transmission Evaluation Project Equipment Comparison, p. 64, Figure 45.

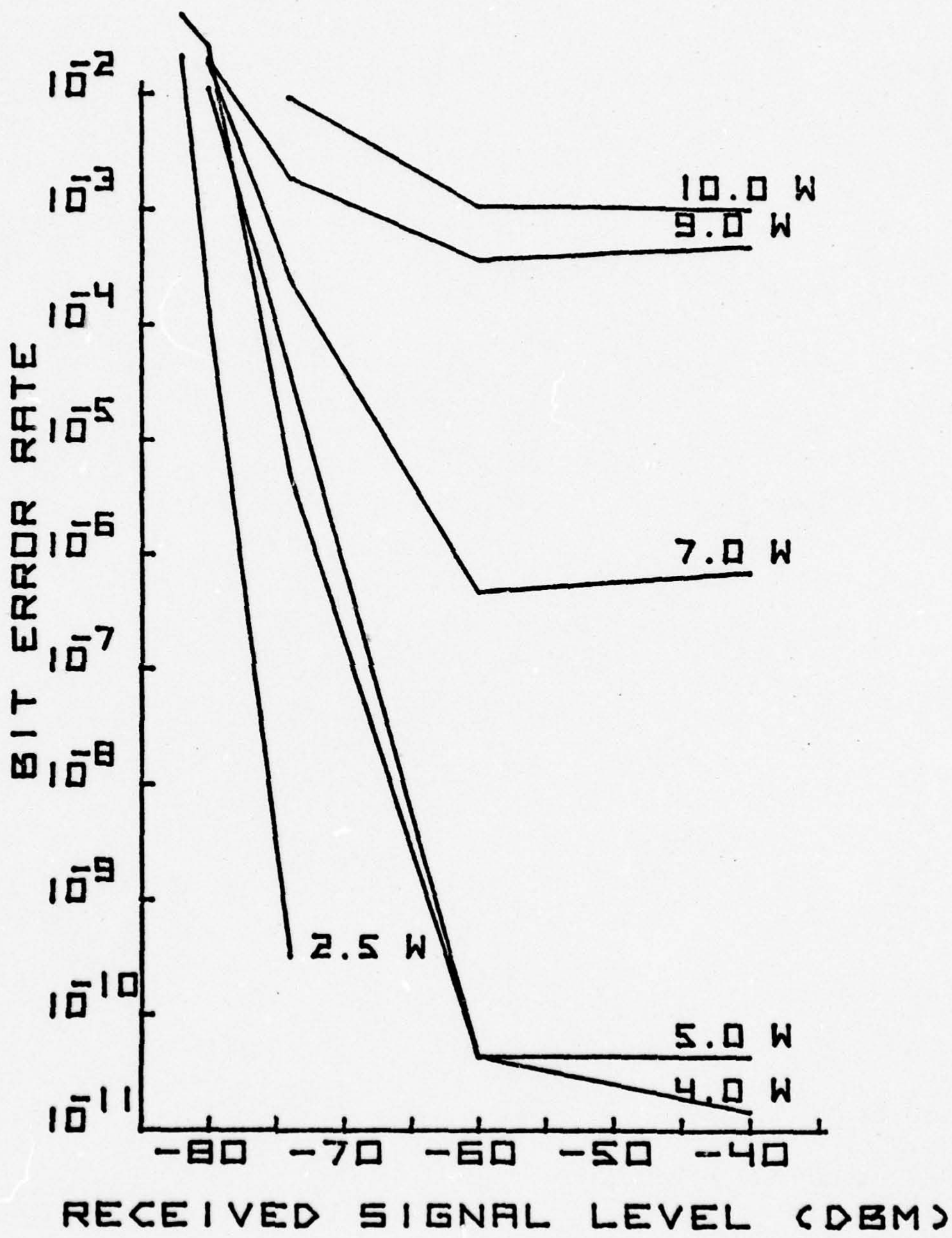


Figure 6-25. Bit Error Rate vs Received Signal Level for Varying Output Power.

Source: Digital Transmission Evaluation Project DR8-A Test Final Report, p. 13, Figure 5.

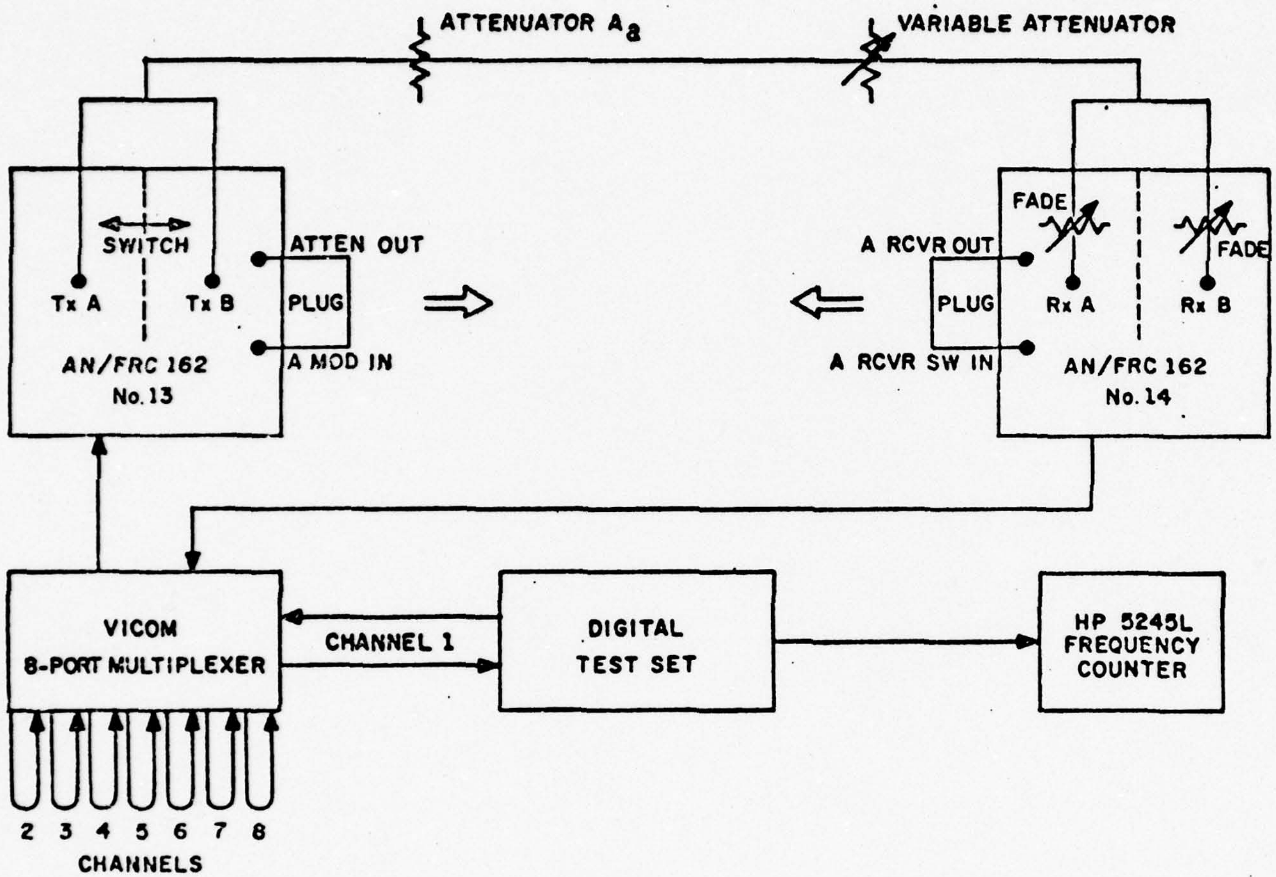


Figure 6-26. Switching Test Configuration

Source: Digital Transmission Evaluation Project, AN/FRC-162 Test Final Report, p. 33, Figure 22.

-66 dBm level is reached the switch must sense another 5 ± 2 dB of difference between the two receivers before the decision to switch to the receiver with the higher RSL. A make-before-break switch arrangement assures a minimum signal interruption and the system operates error free as long as the multiplexer sees no more than a 23 nanosecond delay.

The DTEP also afforded the Military the opportunity to look at link availability with respect to BER over a one hop link and a two hop, non-regenerative, repeatered link. The testing was performed over the 32 mile link established between the test facility at Fort Huachuca and site Sibyl near Benson, Arizona. The two-hop link was established by configuring the equipment at site Sibyl, as a nonregenerative baseband repeater. The significant outcome[37] of the one hop link was that the QPSK radio operated for long periods of time without errors and experienced periodic short duration error bursts. It was promulgated that measuring a link availability of 99% (0.99) could be easily accomplished for a 95% confidence level.[38] Similar tests performed over the two hop non-regenerative baseband repeater link indicated that the BER degraded one order of magnitude over that of a single hop link.[39]

DTEP Summary

The extensive testing and analysis of accrued data during phase I of the DTEP allowed the following developments and conclusions to be made:

1. The development of a field retrofit procedure for the conversion of existing AN/FRC-80 microwave radios from FDM-FM operation to 3-level partial response digital operation.

2. It was concluded that QPSK modulation was the most desirable form of digital modulation where spectral efficiency requirements are not over 1.5 Bits/Hertz.

3. It was concluded that digital transmission was less susceptible to interference than FDM-FM and that within the area of digital transmission QPSK was less susceptable than 3-level partial response or QPR modulation.

Since testing began in March 1974, the Digital Transmission Evaluation Project has proven to be an effective vehicle for the accomplishment of test and evaluation, industry surveys and studies of digital microwave transmission equipments and systems. The program has produced 15 technical reports that provide the indepth detail for the subjects discussed in this section.

For Phase II, the hardware assets ($2.1 million) of the DTEP are configured in a four station, multi-link system to support the Digital European Backbone (DEB) CONUS system testing (the DEB is discussed further in Chapter Eight under Future Digital Systems). This set-up will also be used to evaluate the Digital Radio and Multiplexer Acquisition (DRAMA).

Analysis and Conclusions

Previous DCEO studies of the DCS transmission facilities and equipments indicated that the PCM/TDM approach was the only one that would enable the military to purchase equipment compatible with the evolution of an all-digital system, meet overall system performance objectives, and provide a method of increasing communications security. Results of the above tests established the current technical feasibility and practicality of achieving the objectives through the use of PCM bit streams and bulk encryption. They also showed that increased performance and economies were obtainable in the future.[40]

It was concluded from the tests that the initial implementation should utilize the three-level partial response modulation technique in order to satisfy interim requirements up to 192 channels, maintain the overall system performance objectives of the DCS, and to meet the operationally constrained time frame. In considering the forthcoming tri-service DCS Microwave Radio, it was recognized that a number of technical problems such as signalling and supervision, pilot frequencies, filtering, pre-emphasis and de-emphasis networks, input and output signal levels, combining, and of course, hardware packaging would have to be solved on a design basis first, and then on a production basis. Further encouragement was provided as concurrent common carrier related experience and studies from 1965 thru 1972 supported this interim approach and provided some operational results as discussed in Chapter Seven, Digital Transmission Systems.

The tests clearly showed the need for standardization of equipment and systems tests to identify and establish parameters and techniques to measure equipment and system's performance in standardized ways, as well as a need for better fault isolation methods and procedures.

A further need for the development of adequate and thorough Operation and Maintenance Procedures was recognized to include the training of technical personnel in these new technologies prior to system's implementation.

It was also concluded that additional FDM-FM plant investments would not assist in the desired future transition towards the evolution of an all digital DCS[41] and should be discouraged.

Now, looking beyond the satisfying of low density interim requirements it was apparent that the more efficient types of modulation, such as Quadraphase Shift Keying (QPSK) would have to be implemented in the DCS transmission upgrades as soon as possible in order to realize greater spectrum efficiency and to handle the ever increasing communication's requirements. It had been recognized that digital transmission was much less efficient in spectrum utilization than analog transmission for toll quality voice service. However this was found not to be true when employing the new techniques of QPSK, RF filtering, and the simultaneous use of two polarizations on the same frequency.

It was found that combinations of these techniques achieve bandwidth efficiencies comparable to or better than those of FDM-FM systems for

transmitting analog voice and that when digital data requirements exceed a small percentage of the total traffic, the digital transmission system becomes more efficient than the FDM-FM system.[42]

In conclusion, the tests performed and the contributions of the industrial communications community provided the information necessary to permit a decision to be made concerning the satisfaction of the low density interim requirements by using the three-level partial response technique and bulk encryption as currently available. In the long run, the use of the more sophisticated techniques, such as QSPK is expected to meet the high density future data and voice requirements and can utilize the same or similar encryption equipments.

CHAPTER 6

Footnotes

1. Defense Communications Engineering Office. Preliminary Report: PCM/TDM System Design Verification Test Program. Prepared: February 25, 1972, p. 1-1.

2. Ibid., p. 3-6; 3-7.

3. Ibid., p. 7-18.

4. Ibid.

5. DCEO, Application of Pulse Code Modulation (PCM) Time Division Multiplexing (TDM) and Digital Transmission in the DCS. 7 January, 1972, p. 30 and 38.

6. Ibid., p. 31,32.

7. Air Force Communications Service, Headquarters. DCS Operational Test and Evaluation of PCM/TDM Equipment. Phase I Testing Test Report. September 6, 1973, p.3.

8. Air Force Communications Service, Headquarters. Operational Test and Evaluation of PCM/TDM Equipment. January 1, 1972, p. 1.

9. DCS Operational Test and Evaluation of PCM/TDM Equipment Phase I Testing Test Report, op. cit., p. 83 and 207.

10. HQ Air Force Communications Service. DCS Operational Test and Evaluation of Pulse Code Modulation/Time Division Multiplex (PCM/TDM) Equipment. Test Report, August 1973-February 1974. pp. 4-1 thru 4-3.

11. DCS Operational Test and Evaluation of PCM/TDM Equipment Phase I Testing Test Report, op. cit., p. 138-139.

12. DCS Operational Test and Evaluation of Pulse Code Modulation/ Time Division Multiplex (PCM/TDM) Equipment. Test Report, August 1973-February 1974, op. cit., pp. 5-1 through 5-5.

13. Richard E. Skerjanec, OT TM 73-137C, Test Results for Digital Testing of the Candidate Radios for the DCS Microwave Radio, Institute of Telecommunications Sciences, April 1973, p. 65.

14. Ibid., pp. 2, 22, 46.

15. Ibid., p. 45.

16. United States Army Strategic Communications Command, Concept Plan for PCM/TDM Digital Transmission Application Project (DTAP) Engineering and Operational Testing, May 1972, p. i.

17. Ibid., p. 1.

18. Ibid., p. A-11.

19. Ibid., pp. A-5 to A-7.

20. Ibid., pp. A-5 to A-7.

21. Headquarters, U.S. Army Strategic Communications Command, Program Concept Plan for the Digital Transmission Evaluation Program (DTEP), (August 1973). p. 4.

22. Headquarters U.S. Army Communications Command, CE Project Communications, Electronics Mission Order for the Digital Transmission Evaluation Project, (October 1973). p. 4.

23. Ibid., pp. 13-14.

24. Cpt. James E. Hamant, Cpt. Harold F. Bower and 1LT Edward F. New, Digital Transmission Evaluation Project Equipment Comparison: BER vs RSL, C/I, Power Spectra Special Report, (August 1975), p. 5.

25. Cpt. James E. Hamant, Cpt. Harold F. Bower and 1LT Edward F. New, Digital Transmission Evaluation Project MW-518 (QPSK) Test: Final Report (October 1975), p. 14.

26. Cpt. Harold F. Bower and 1LT Edward F. New, Digital Transmission Evaluation Project RDS-80: Final Report, (May 1975), p. 12.

27. Cpt. Edward F. New, Digital Transmission Evaluation Project AN/FRC-162 Test Final Report, (May 1976), p. 14.

28. Cpt. Harold F. Bower, 1LT Edward F. New, David M. Laida and Arnold Hemila, Digital Transmission Evaluation Project: RDS-80G Final Report,(February 1975), p. 18.

29. Cpt. James E. Hamant, O.P. Connell and Henry S. Walczyk. Digital Transmission Evaluation Project DR8A Test Final Report, (April 1977) pp. 12-20.

30. D. Smith and F.G. Kimmett, Measurement of Interference Effects between TDM-FM and FDM-FM Microwave Systems, (March 1975), pp. 38-39.

31. J.E. Farrow and R.E. Skerjanec, ITS. AN/FRC 80(v)3 Retune and Time Division Multiplex Interface Investigation,(October 1974), pp. 38-85.

32. Ibid., p. 85.

33. Capt. James E. Hamant, Cpt. Harold F. Bower and 1LT Edward F. New, Digital Transmission Evaluation Project Equipment Comparison BER vs RSL C/I, Power Spectra Special Report, (August 1975), p. 78.

34. Cpt. James E. Hamant, O.P. Connell and Henry S. Walczyk Digital Transmission Evaluation Project DR8A Test Final Report, (April 1977), p. 10.

35. Cpt. Edward F. New, Digital Transmission Evaluation Project AN/FRC-162 Test Final Report, (May 1976), pp. 32-36.

36. 1LT Edward F. New. Digital Transmission Evaluation Project 23 P2B Sensor Logic Switch Test Final Report, (Sept. 1975), pp. 32-36.

37. Cpt. Harold F. Bower, 1LT Edward F. New, David M. Laida and Arnold Hemmila, Digital Transmission Evaluation Project RDS-80 G Test Final Report, (February 1975), p. 14.

38. Ibid., p. 16.

39. Cpt. Edward F. New, Digital Transmission Evaluation Project. AN/FRC-162 Test Final Report, (May 1976), p. 39.

40. Defense Communications Engineering Office, Application of Pulse Code Modulation (PCM), Time Division Multiplex (TDM) and Digital Transmission in the DCS, 7 January 1972, p. 5.

41. Ibid., p. 6.

42. Ibid., p. 21.

CHAPTER 7

DIGITAL TRANSMISSION SYSTEMS

Inspired by a growing demand from digital users, yet constrained by the limits of allocated and available RF bandwidth, and a large inventory of physical analog plant, the telecommunications industry made important progress during the early seventies toward satisfying the requirements for increased traffic density, improved message handling and switching capability, faster data rates, and the ability to provide privacy and secure communications.

Significant advances had been made in the promising arts of fiber optics and light emitting diodes (LED's), millimeter waves, and satellite communications. New and improved electronic systems employing the medium-scale integration (MSI) and large-scale integration (LSI) technologies, along with new software programs and techniques, were being utilized for terminals, branch exchanges, and switching centers.

Improvements in microwave digital transmission and the development of wideband data modems were also major contributors to this growth trend. Many of these improvements were due to advancements in key active device technology which provided new and better ways to solve old hardware and system design problems.

The appearance of the Gunn and IMPATT diode microwave power sources for use in high capacity microwave systems illustrates this point. Gunn diodes provided the much sought after low noise advantages necessary for higher frequency oscillator designs. The IMPATT diodes permitted designers to achieve solid state amplifier power outputs of up to three and one-half watts,[1] compared to the one-half watt (+27 dBm) of previously designed solid state amplifiers.

These devices performed exceptionally well at frequencies above 5 GHz and were immediately used in such hardware applications[2] as the 11 GHz, TN-1 repeater equipment developed by Bell Laboratories, and the FH and FV repeater series, for the 6 and 13 GHz bands, built by Farinon Electric.

During the same time period, notable improvements were made in digital microwave transmission efficiency. Avantek offered a 2 GHz radio which could carry 12.6 Mbps and had an emission spectrum bandwidth of only 7 MHz. Microwave Associates offered an 11 GHz radio which would carry 79.2 Mbps within an assigned spectrum bandwidth of only 40 MHz. This later system provided for the transmission of up to 1152 voice frequency channels on a single polarization.

In mid 1973, the Assistant Secretary of Defense (Telecommunications) and the Director, Defense Communications Agency, directed that future transmission upgrades and extension projects within the Defense Communication System would utilize digital transmission.[3]

It was concluded in Chapter Six that (1) bulk encryption and the evolution of an all digital system could, at this time, be only obtained

through the use of PCM/TDM, (2) the medium density, 192 channel, interim requirement could be satisfied only by the use of three-level partial response hardware because of operational time constraints, (3) the technical problems associated with the system application of three-level partial response, as described in Chapter Six, would have to be resolved prior to production, and (4) the need existed for system performance standards, fault isolation techniques, Operation and Maintenance (O&M) procedures, and personnel training.

In view of these conclusions, the technological advances mentioned above, and the guidance given by the Office of the Secretary of Defense in regard to bulk encryption, the DCA and the MILDEPS examined several existing commercial systems for insight into any system's design, implementation, or performance problems prior to the development and implementation of a pilot digital program to satisfy the requirements of the Frankfurt-Koenigstuhl-Vaihingen (FKV) System.

The commercial systems examined were:

(1) The Microwave Communications Incorporated System (MCI) which was engineered and installed jointly by Microwave Communications of America, Inc. (MICOM) and Raytheon.

(2) The Albany - Troy RDS-80 Digital Microwave Transmission System of the New York Telephone Company, which was engineered, furnished, and installed by Raytheon.

(3) The Data Transmission Corporation (DATRAN) System.

Each of these system evaluations contributed in different ways to the Military's management and technical knowledge base. The MCI system discussion is more management oriented, but does briefly touch upon the utilization of analog technology and techniques available for accommodating the transmission of digital information. The discussion of the Albany-Troy RDS-80 Digital Microwave Transmission System is basically concerned with the New York Telephone Company's injection of a microwave link into the middle of an existing traffic-carrying cable system to determine interface compatibility, and the extraction of technical data to determine system performance parameters for utilization in design of future systems. The DATRAN system discussion is a blend of these two facets--encompassing the application of state-of-the-art digital technologies, regulatory problems, new methods of managing information-transfer, and, unfortunately, the collapse of a business venture in a very competitive commercial and military market. The chapter closes with an in-depth discussion of the Military's transitional digital system (the Frankfurt-Koenigstuhl-Vaihingen System), which encompasses the technical, regulatory, and implementation problems encountered.

The Microwave Communications Inc. (MCI) System

The concept of what is now called the special service common carrier was conceived in the early 1960's by John Goeken, the President of Microwave Communications Inc. (MCI). "Goeken saw a need for many small business companies to be able to effectively have the advantage of

their own private microwave system."[4] Although regulatory policy permitted private companies to construct their own private systems, the large initial investment in establishing such a private microwave system meant that only the larger companies could afford to do so. Thus, it was for those who could not individually justify their own private system, that Goeken's plan was conceived. The large number of individually small requirements of such companies would add up to a large number of channels which must be planned for to obtain economical per channel costs.

The Evolution

Obtaining authorization for such a system proved to be a long and arduous task. Although MCI applied in 1963 to the FCC for authority to construct the Chicago-St. Louis portion of the system, hearings were not held until early 1967. It was not until late fall that the FCC's Common Carrier Bureau and the Hearing Examiner recommended the granting of construction permits. Further objections and subsequent oral arguments delayed the granting of the license until August of 1969. At that time the FCC granted MCI a license for a common carrier system between Chicago and St. Louis. Subsequently, Microwave Communications of America, Inc. (MICOM) was selected to perform the site selection and path engineering, while the Raytheon Company was awarded the contract for system implementation.

Today, MCI[5] is a $100-million-plus group of corporations with a nation-wide netword offering a wide variety of channels of various bandwidths

to any customer who can use them. The MCI Carriers are MCI Indiana-Ohio, Inc., MCI Kentucky Central, Inc., MCI Michigan, Inc., MCI Mid-Atlantic Communications, Inc., MCI Mid-Continent Communications, Inc., MCI Mid-South, Inc., MCI New York West, Inc., MCI-North Central States, Inc., MCI Pacific Coast, Inc., MCI St. Louis-Texas, Inc., MCI Pacific Mountain States, Inc., MCI Southeast Communications, Inc., MCI Texas East Microwave, Inc., MCI Texas-Pacific, Inc., MCI New England, Inc., and Microwave Communications, Inc.

MCI's prices, like those of the other specialized carriers, were attractively lower than those of the established carriers, and consequently, AT&T complained bitterly that MCI was being allowed to "cream skim," that is, to provide service only to those parts of the country where there would be a maximum profit. In contrast, the Bell System had to provide any given type of service to customers in any part of the country regardless of population density.[6] Although MCI was described initially as a non-telephone common carrier, it was soon apparent its major source of business revenue was from "corporation to corporation telephone service," and this fact strongly influenced the thrust of MCI's marketing strategy.

Thus, MCI had successfully launched a new industry and had become the first of a new breed of specialized common carriers which do not install telephones or teletype machines, but provide unique transmission facilities to any buyer.

Subsequently, the FCC has been besieged with almost 2,000 micro-wave applications for specialized purposes, including data transmission.

Finally, in 1971, in the face of bitter opposition from AT&T, the FCC Commissioners ruled favorably on the concept of specialized common carriers. As expected, a tough competitive industry emerged from that decision.

The MCI System

The system as conceived was to be a nation-wide, specialized common carrier network, employing microwave analog transmission, principally in the 6 GHz band using 1800 channel analog microwave transmission equipment. The initial backbone microwave transmission system was analog in nature, with the use of modems to convert an increasing percentage of digital data into analog form. At the time the construction permit was granted, and as discussed in Chapter Four, there were many unknowns with respect to microwave digital transmission. Foremost perhaps, was the issue of interference to existing and contemplated FDM-FM microwave systems by digital transmission systems. Another problem was that of the emission bandwidth of such systems. The point was made that a PCM microwave system having a capacity of only 480-4 KHz voice channels, and an FDM microwave system having a capacity of 1200 to 1800-4 KHz voice channels would occupy nearly equal bandwidths.

Because of these and other concerns, the MCI system utilized the Raytheon KTR-3A frequency diversity FDM-FM microwave equipment, having a capacity of 1800 voice frequency (VF) channels. The KTR-3A was a field proven, completely solid state radio (except for the traveling wave tube amplifier (TWT) which could provide up to ten watts of output

power). To facilitate repeater drop and insert capability, a special modulatable solid state microwave source was used with each transmitter allowing up to 120 voice channels to be inserted in each repeatered direction.

The alarm and orderwire system was translated up and onto a single sideband (SSB) carrier operating above the baseband spectrum. This provided up to 16 station alarm and status conditions, local orderwire, and express orderwire functions.

The analog multiplex equipment utilized in the system was North Electric's MA-5, which could interface with standard data modems without accessory equipment. In addition to the conventional 4 KHz voice frequency channels offered by MCI, the equipment would accommodate analog signals with bandwidths of 12 KHz, 48 KHz, and 240 KHz. Furthermore, the equipment had provisions for baseband spectral bandwidths to suit a range of digital speeds between 75 and 19,200 bps, and a variety of other types of channels of different nominal bandwidths. All of these added equipment capabilities were intended to provide a digital data transmission capability via an analog system.

The antennas utilized were Prodelin High Performance Dual Polarized parabolic dishes, varying in diameter from 8 to 15 feet, and some specially designed antennas for critical paths. The system was implemented with dual polarization, even though initially, only one polarization was utilized on each path. This was done to provide system flexibility and growth. Additionally, the towers were designed to accommodate

AD-A051 789 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO F/G 17/2.1

MILITARY DIGITAL MICROWAVE TRANSMISSION: PAST, PRESENT, FUTURE.(U)

AUG 77 R E BRACKETT, W E CARTER, J J SOLTIS

UNCLASSIFIED AFIT-CI-78-45 NL

3 OF 4

AD

A051789

future antenna load increases (tortional twist and sway), including provisions for tails and spurs, and for a reversion to space diversity if the need arose. Some problems were encountered due to interference with other systems, thereby necessitating the development of special antenna radiation patterns to provide the requisite isolation from other existing and future systems.

Of notable interest to the MILDEPS was the treatment of frequency coordination. MCI employed Spectrum Analysis and Frequency Planning Inc. (SAFP) to produce a frequency plan which ensured freedom from interfering signals and minimized the effects on adjacent systems. The SAFP data base contained an index of over 10,000 microwave sites or stations for which licenses had been applied or granted. The data included antenna type and location, power output, frequency, polarization and radiation pattern.

Upon completion of the proposed system layout, site selection, and determination of frequencies, a computerized interference analysis was performed with particular emphasis on co-located sites and closely spaced parallel paths to determine all possible combinations which might produce interference. The paths where interference was not expected to be a problem were accepted, and those that were likely to cause interference, or were interfered with, were examined further, and various solutions put forth. Where it was possible to solve the problem with greater antenna off-beam discrimination, more directive antennas were proposed. Where no other course of action was feasible, site relocation was considered.

In July 1977, the new MCI president, Orville Wright, announced a $30 million construction and capital equipment expansion and modernization program. The program includes network expansion to add Columbus, Dayton, and Cincinnati, Ohio to the network by September; a new parallel radio route between New York and Boyertown, Pennsylvania (interconnecting with MCI's main East-West line); a new terminal in Southfield, Michigan to be operational in December 1977; an increased capacity in the amount of an additional 2100 VF circuits between New York and Chicago, St. Louis and Dallas, Philadelphia and Washington, and Chicago and Omaha; and the installation of new computer controlled electronic switching equipment in 12 more cities, thereby making a total of 17 cities with MCI electronic switch capability, and over 38,000 circuits which are computer controlled through electronic switches.[7] This is an astounding expansion for a system which has been in operation only a little over five years!

In conclusion, the far sighted Goeken had seen an immediate market for corporate analog services with small and growing needs for digital service. Most importantly, he had recognized that the problems of digital microwave transmission would arouse bitter controversy. He wisely chose to avoid that controversy and gambled on being able to satisfy the increasing needs for digital information transmission through the use of A/D and D/A converters. Another problem was that of obtaining sufficient spectrum allocation to keep abreast of the demand. The initial use of dual polarized antennas, coupled with good engineering, provided redundant use of the assigned spectrum, and enough bandwidth versatility

in the multiplex and radio equipment to allow this to happen. Gocken's timeliness, wisdom, and foresight allowed MCI to become a staunch competitor in an industry within which, little or no competition had been felt for decades.

The Albany-Troy RDS-80 Digital Microwave Transmission System

During November 1971, Raytheon installed an RDS-80 Digital Microwave Transmission System between Albany and Troy, New York. The purpose of the installation and subsequent testing was to evaluate the overall system's performance of the digital radio with an associated digital cable interconnect system, and a digital multiplexer with a T1 line (1.544 Mbps) input and output.[8] The tests included measurement of emitted spectrum bandwidth, examination of interference criteria, re-use of the same microwave frequency by means of cross polarization, system performance parameters, and implementation of a hot standby protection system. The system was operated on Experimental (Developmental) License KB2XZF granted by the FCC in August, 1971.

The Albany-Troy Test Bed

The RDS-80, 11 GHz digital Transmission System was completely solid state, and was configured in two standard 19 inch wide racks 7½ feet high as shown in Figure 7-1. The radio rack contained two complete transmitters and receivers, with a third transmitter-receiver used as a 1-for -2 hot standby. Each rack also contained display, control, and

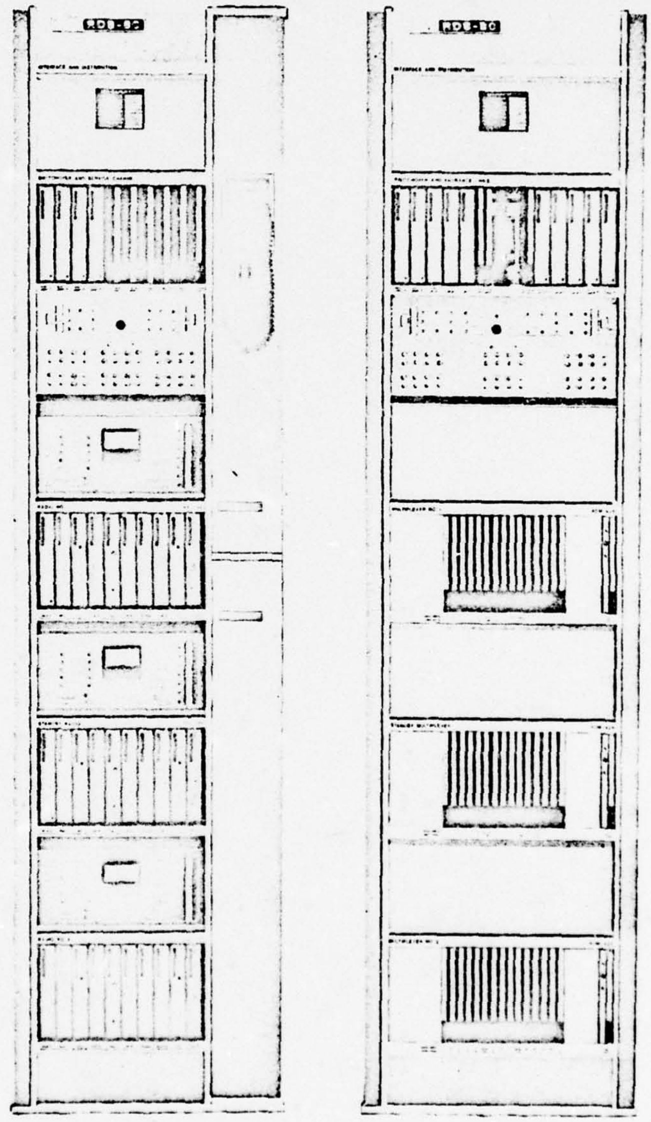


Figure 7-1. RDS-80 Digital Transmission System Equipment.

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 1-1, p. 1-2.)

automatic switch-over circuits.[9] Figure 7-2 shows a block diagram of the system. Each of the radio-multiplex combinations could handle up to 600 VF channels or 25 T1 lines; if two radios were to use orthogonal polarizations on the same antenna, the combination could handle 1200 voice channels. Since this was the first look for the Military at an 11 GHz digital radio employing a QPSK (Quadrature Phase Shift Keyed) modulator, the operation was of considerable interest with respect to its suitability for use in the DCS. The detailed theory of operation is described in Appendix A, RDS-80 System Theory of Operation.

Digital Testing, System Performance Parameters

The Albany-Troy system tests were performed during 1972; the tests were run in much the same manner as were some of the tests performed by the Military described in Chapter Six. Typically, a pseudo-random sequence was generated and applied to one of the 25 T1 input channels of the multiplexer. This channel was monitored at the far (receiver) site by a pattern detector and an electronic counter (HP5245L) was used to accumulate and display bit errors. Numbers of errors per unit time were recorded and displayed on a chart recorder.

Initially, the system utilized only a vertically polarized antenna feed, but the feed was changed to a dual polarization feed in early 1973 to permit bit rate capability to be expanded to 80 Mbps.

A Bit Error Rate (BER) threshold of 10^{-7} had been established for the RDS-80 System, since that was at least an order of magnitude

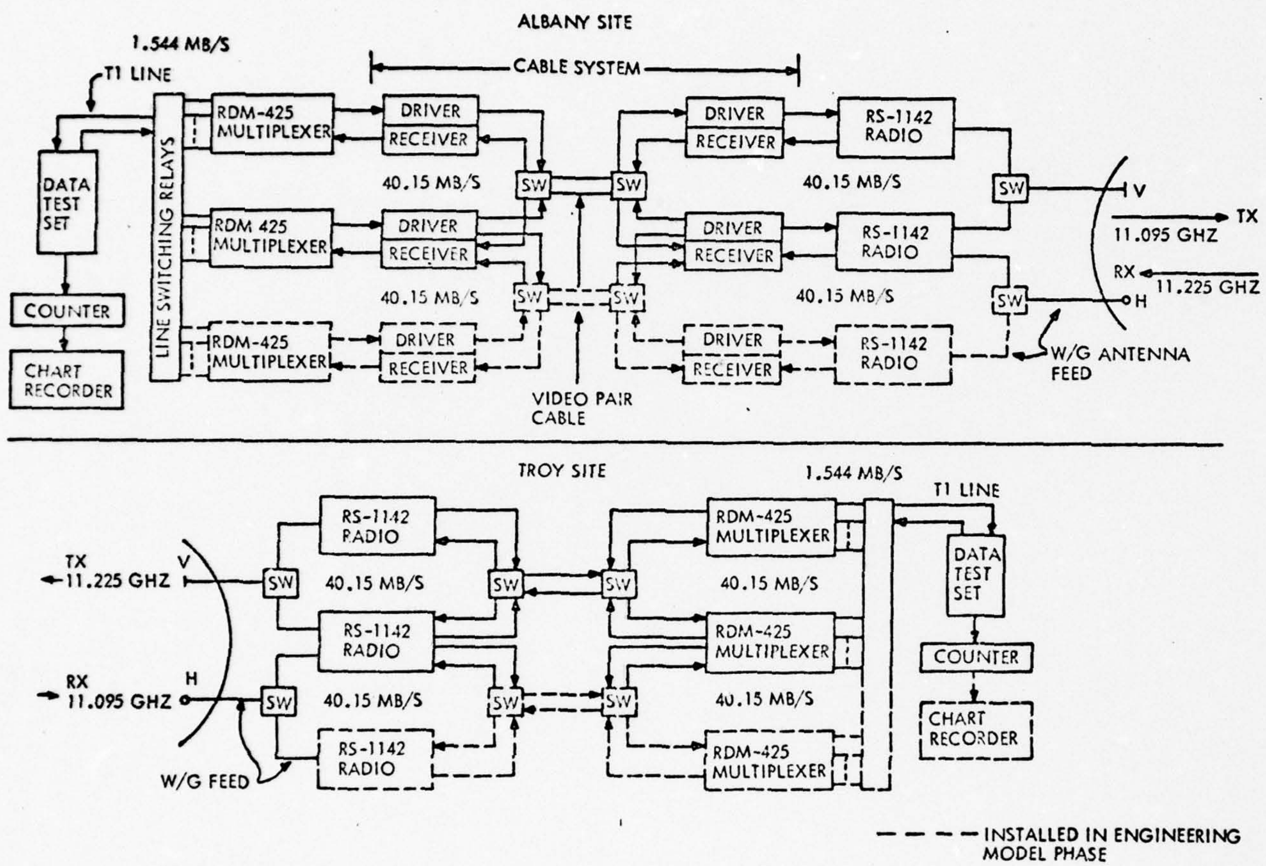


Figure 7-2. Albany Troy RDS-80 Digital Transmission System, Block Diagram

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 2-1, p. 2-2)

better than the required end-to-end circuit specification for a digital channel. The received carrier input level specification for a BER threshold of 10^{-7} was calculated to be -73 dBm at the mixer input.[10] Since BER was the most important performance parameter of a digital communications system, exhaustive tests were made by further attenuating the signal in the antenna feed waveguide to simulate path fading in both directions of transmission simultaneously. This was accomplished by calibrating the transmitter power and received carrier level at each site on a clear day, and then inserting the attenuation in 1 dB steps to obtain the threshold characteristic as shown in Figure 7-3. In this scatter plot, the BER data between 10^{-3} and 10^{-7} was based on an error count over a 30 second period at each received carrier level tested, whereas between 10^{-8} and 10^{-9} data was measured by counting errors over a five minute (300 second) interval to obtain reasonable confidence levels. Although not reflected on the scatter plot, 24 hour tests, and BER counts greater than 10^{-9} were made without recording any errors at normal high signal levels. As seen in the scatter plot, the performance objective of a BER threshold of 10^{-7} was essentially achieved.

Examination of the plotted Receiver Sensitivity Characteristic, Figure 7-4, showed a very rapid improvement in BER for only a few dB increase in carrier level. The steepness of the threshold characteristic is of prime importance when establishing the end-to-end bit error rate objective of the system. If, as before, the system bit error rate

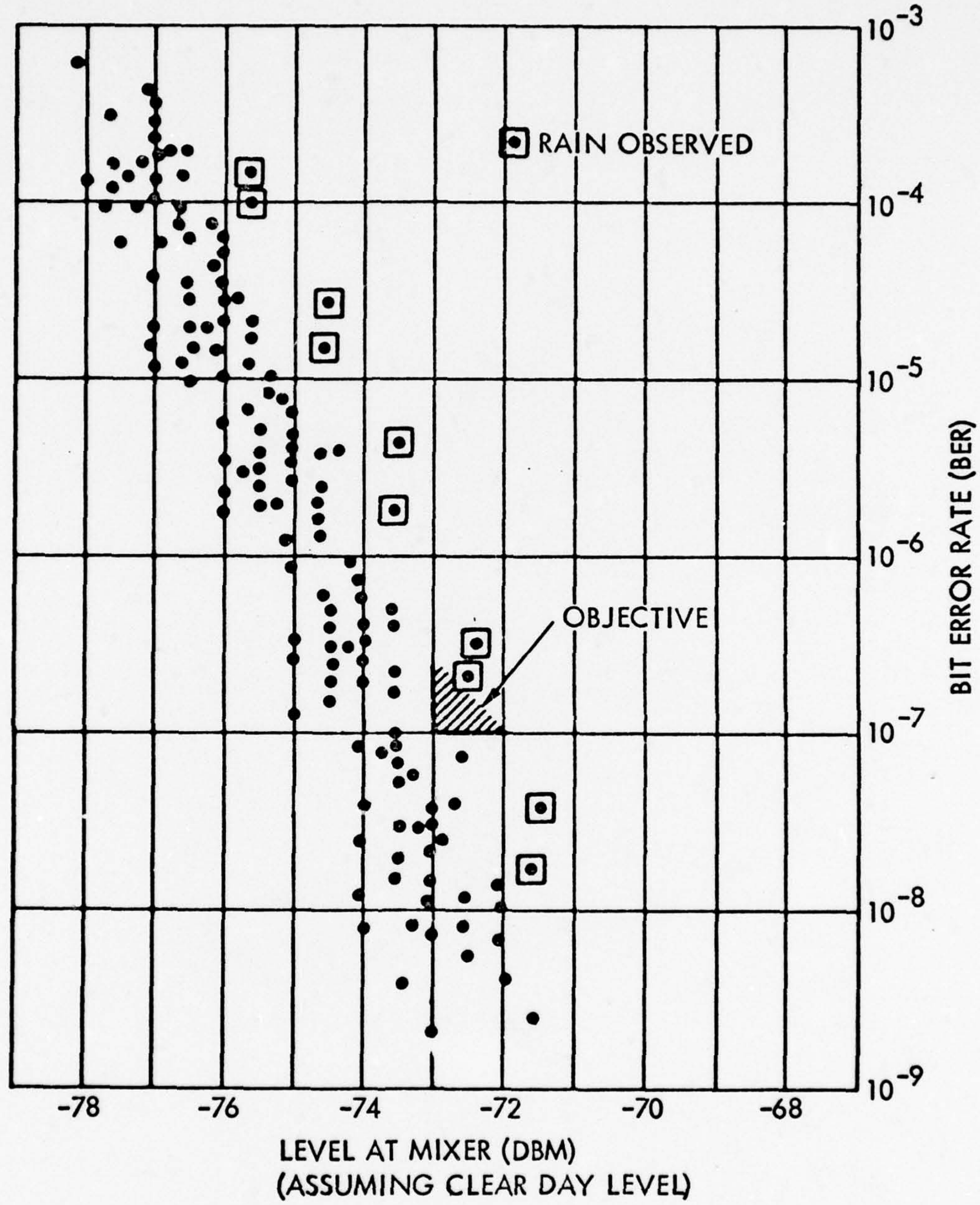


Figure 7-3. Scatter Plot of 25 Threshold Runs Measured Between 9/11/72 and 9/15/72, Albany-Troy System

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 4-1, p. 4-3.)

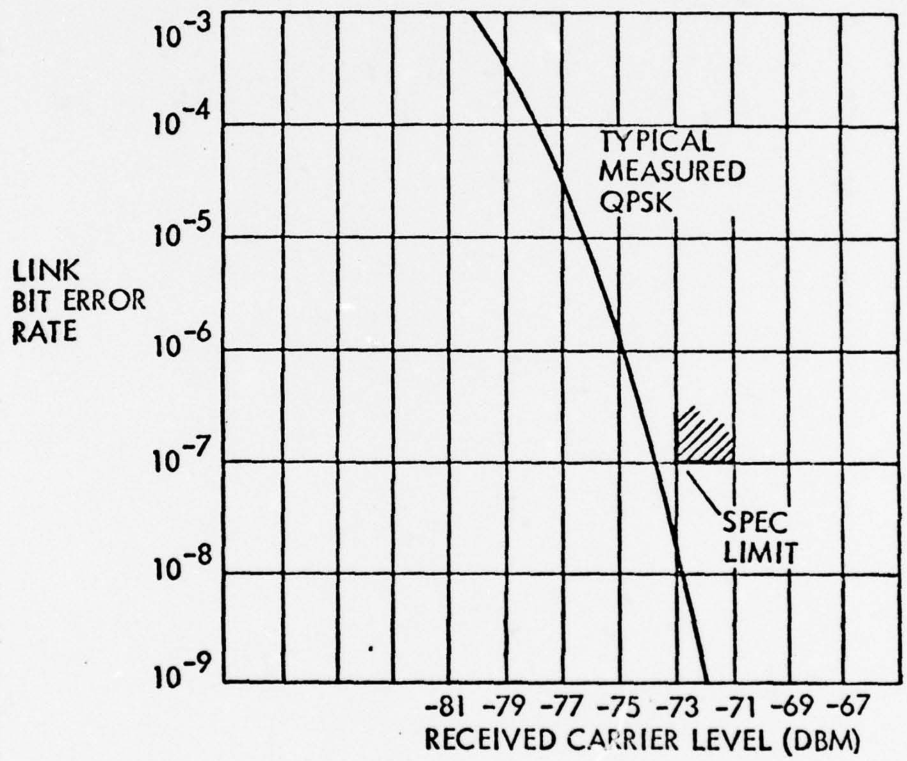


Figure 7-4. RDS-80 Receiver Sensitivity Characteristic

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 4-2, p. 4-4.)

objective was 10^{-7}, and the RDS-80 system was comprised of a 10 hop system, it can be seen from Figure 7-4 that an additional system margin of only 0.75 dB per hop is required to achieve a per hop bit error rate objective of 10^{-8}. This would satisfy the end-to-end systems requirement of 10^{-7}. Thus, only a very small amount of additional fade margin is required on each hop to obtain the requisite single hop performance.[11]

However, it should be noted, that the typical 35 or 40 dB fade margin utilized for FDM-FM systems will generally result in a better median noise level in the digital system voice channel. This is primarily due to the fact that, in an FDM-FM system, the distribution of the voice channel noise is a function of the received carrier level above threshold. In a digitally modulated carrier system, the voice channel noise after demultiplexing is basically independent of the received carrier level when it is above threshold.

Analysis of the tests and data with respect to signal fades revealed that a digital system exhibits very different characteristics from an FDM-FM system. At high signal levels, the FM system generally exhibits a somewhat better performance than a digital system because of the quantization noise, which in turn, is due to the PCM coding process used in the digital system. This noise contribution occurs only as frequently as the voice signal is digitized. This digitizing need be done only once so that multihop systems will not have cumulative noise build-up.

A channel at the top portion of the baseband in an FM system was

found to degrade linearly in signal to noise ratio with decreasing RF signal level down to the point at which the voice channel is considered unusable (55 dBrnCO of noise). A channel at the bottom of the baseband degrades linearly with decreasing signal level down to FM threshold, but below that point, the channel noise increases rapidly. The digital system, however, exhibited no degradation with decreasing signal level until an error rate of 10^{-7} or worse, was reached. Further drop in signal level caused the system to degrade rapidly to 55 dBrnCO, at which point the system "crashes" and the effect is present in all the demultiplexed voice channels.[12]

In summary, for the RDS-80 digital system:

1) There is no performance degradation until the signal level fades below a known threshold. Thus, performance is affected only by deep fades, which have a low probability of occurrence.

2) All channels contained in the digital baseband exhibit the same increase in noise with fading.

In conclusion of this section on system's performance parameters, it was shown that for the same link and link fade margin, the RDS-80 System required from 8 to 9.5 dB less power to meet the same FDM-FM voice frequency channel noise objectives.

<u>Digital Testing-Cross Polarization</u>

The cross polarization tests were first performed in the laboratory where the Carrier to Interference Ratio (C/I) was carefully measured.

Additionally, bit error rate measurements were made on a 1.5 Mbps channel while the interfering carrier was modulated at 40 Mbps by a separate test signal generator. The results of these tests are given in Figure 7-5, BER versus Receive and Carrier Level for Different Values of C/I, and Figure 7-6, Receiver Threshold Versus Cross Polarization Isolation for BER = 10^{-7}.

System dual polarization tests were then performed, and successfully showed that an operating system would not be significantly affected by the use of dual polarization. The measured "cross-pol" isolation was 32 dB and the receiver threshold curves for both the standby and hot receivers were plotted, and found to track within 0.3 dB. It could thus be easily concluded upon examination of Figure 7-7, Dual Polarization Threshold Test, that an operating RDS-80 system is not significantly degraded when cross polarization is utilized. A third test on long-term BER was performed over a simulated four hop, dual polarized system. Over one month's collection of data revealed a median system BER of 10^{-10}, and a 24 hour median BER of 10^{-8}.

The success of these tests is probably attributable to the good design techniques employed in the RDS-80 to allow cross polarization operation. It employs a coherent recovery technique in the demodulator and has excellent carrier frequency stability. Additionally, the RF and IF filters were selected to minimize intersymbol distortion.

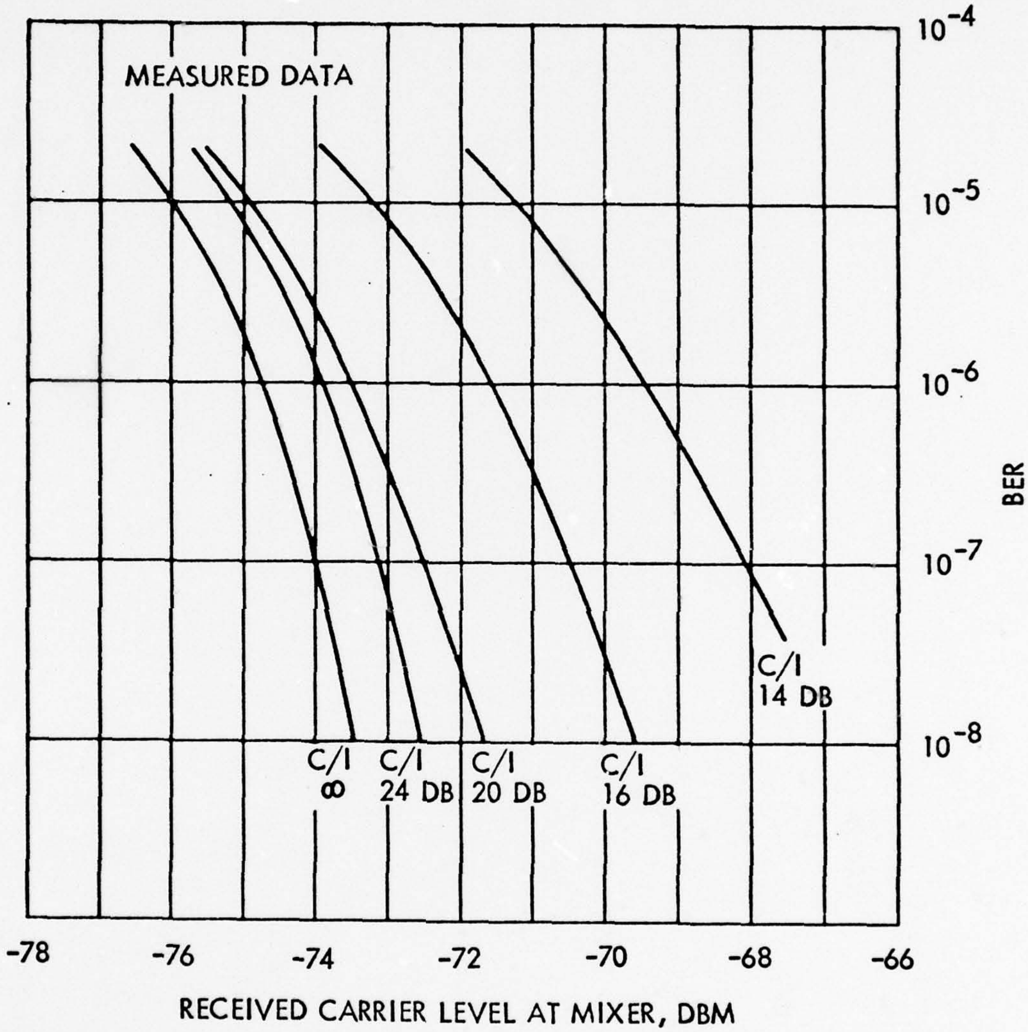


Figure 7-5. BER Versus Receive and Carrier Level for Different Values of C/I.

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 5-1, p. 5-2.)

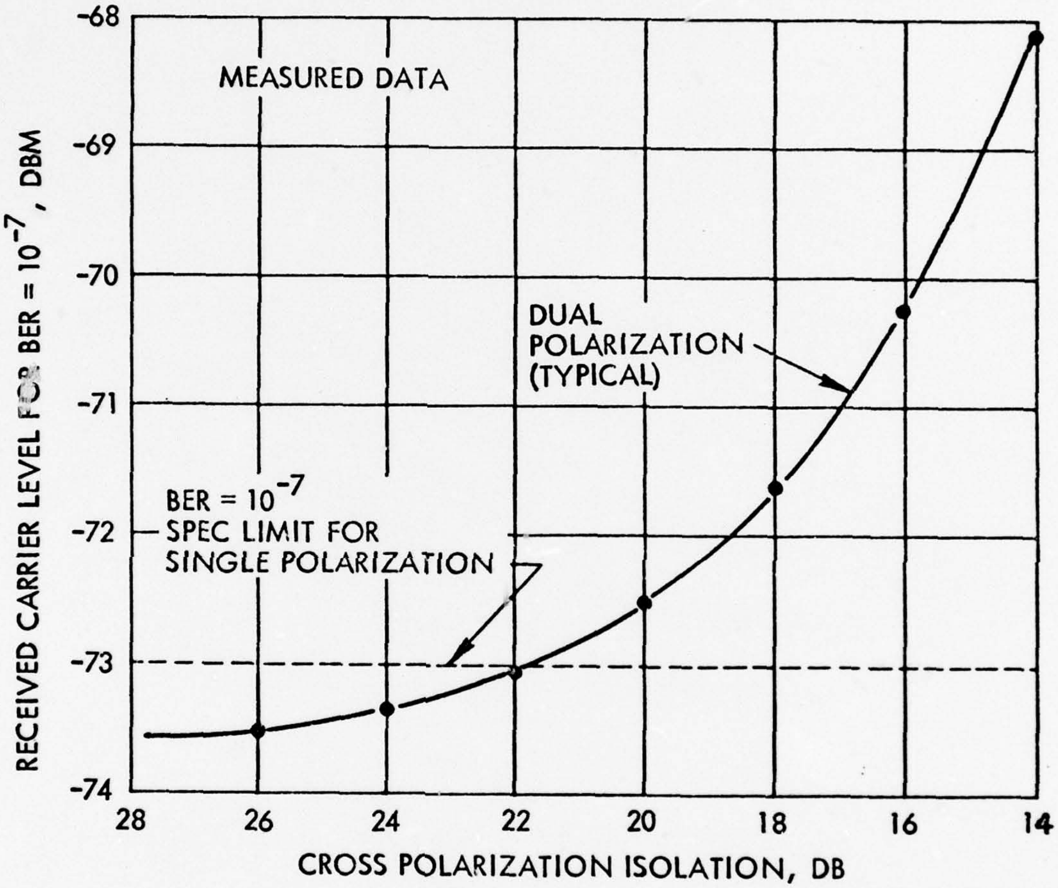


Figure 7-6. Receiver Threshold Versus Cross Polarization Isolation for BER=10^{-7}.

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 5-2, p. 5-3.)

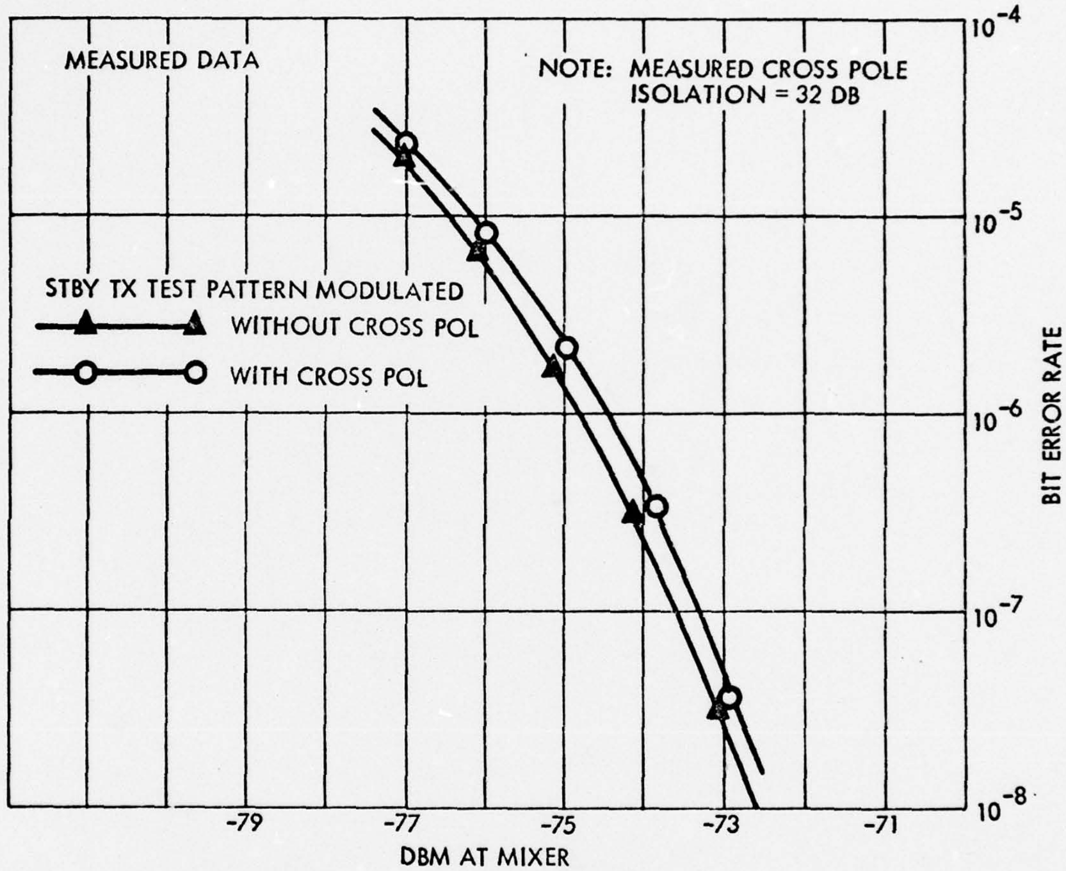


Figure 7-7. Dual Polarization Threshold Test

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 5-3, p. 5-5.)

Digital Testing-Interference and Emission Spectrum

The purpose of these tests was to determine the extent of interference produced by the RDS-80 system into co-channel and adjacent channel FDM-FM systems. As discussed in Chapter Four, the Military and Spectrum Allocation, the interference problem was perhaps exaggerated by the lack of adequate technical data. The data gathered in these tests, and in the tests reported by J.E. Farrow, R.E. Skerjanec, in OT Technical Memorandum 74-182, and D. Smith, F.G. Kimmett, in OT Technical Memorandum 75-194, formed the basis for many good engineering decisions, and allowed future planning and programming to be based on facts previously not available to engineering and systems managers.

The co-channel test was performed by connecting an FM 600 channel system with a top baseband frequency of approximately 2.5 MHz to one polarization of the antenna system, and the digital system, RDS-80, to the other polarization (note that this interference test includes both the effects of the radio system discrimination as well as polarization discrimination). Interference levels were varied by attenuating the RDS-80 transmitted signal, while simultaneously measuring voice channel noise (in dBrnCo) in equivalent channel slots throughout the FM receiver baseband. Analysis of the resultant data of the co-channel tests (Figure 7-8, Co-Channel Interference Test Results) showed variation in voice channel noise at various points in the FM receiver baseband with respect to the

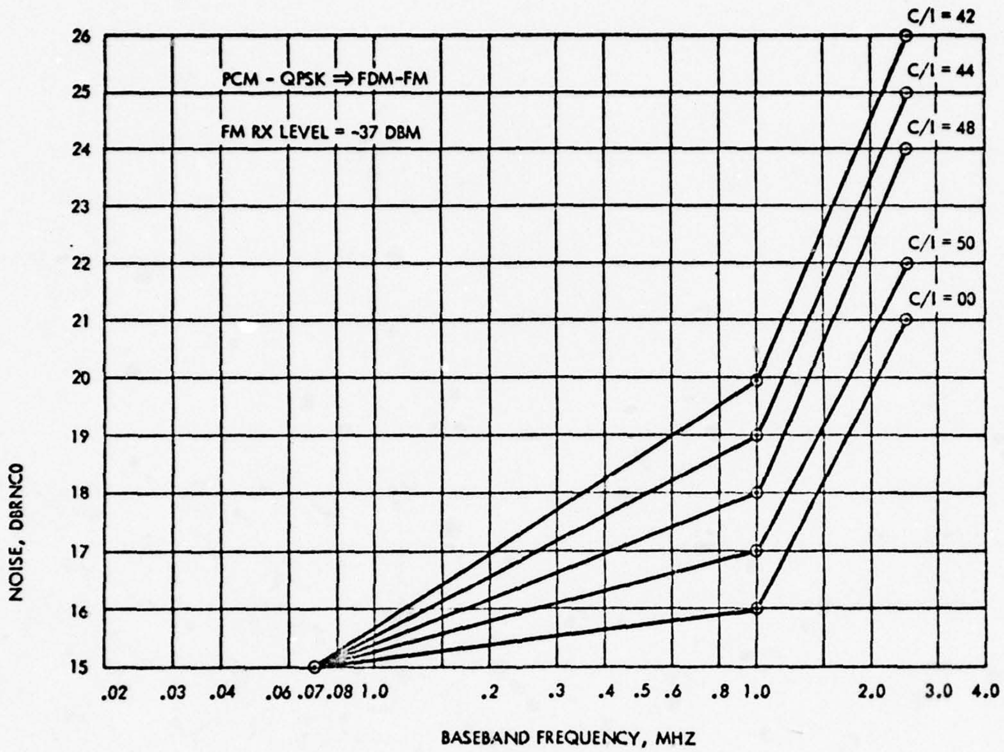


Figure 7-8. Co-channel Interference Test Results.

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 7-3, p. 7-4.)

carrier to interference ratio (C/I). Perhaps the most significant result of the test was that a C/I = 50 dB (including cross polarization isolation) caused a 1 dBrnCo increase in voice channel noise in the most sensitive channels.

The adjacent channel interference tests utilized the same FM and digital systems as above, connected to the same polarization of the same antenna system, but the digital (RDS-80) transmitted frequency was offset 40 MHz from the FM receive frequency. As before, the voice channel noise in dBrnCo was measured in various voice channel slots throughout the FM receiver baseband for different values of C/I. An extrapolation of the resultant data taken at 2.5 MHz (Figure 7-9, Adjacent Channel Interference Tests Results) indicated that the carrier to interference ratio that causes a 1 dBrnCo increase in voice channel noise in the most sensitive channels was approximately 5.5 dB.[13]

A Staggered Frequency Plan Interference Test was also performed for the situation where crossing routes or paths are encountered. Similar results on voice channel noise were obtained.

At that period of time, the most worrisome aspect of the frequency coordination-problem seemed to be that of the digital radio interfering with the analog radio. Therefore, the transmitted spectrum of the digital system had to be adequately contained by stringent RF filtering. Additionally, since the RDS-80 was designed to achieve a transmission rate of 80 Mbps by using both planes of polarization, polarization isolation

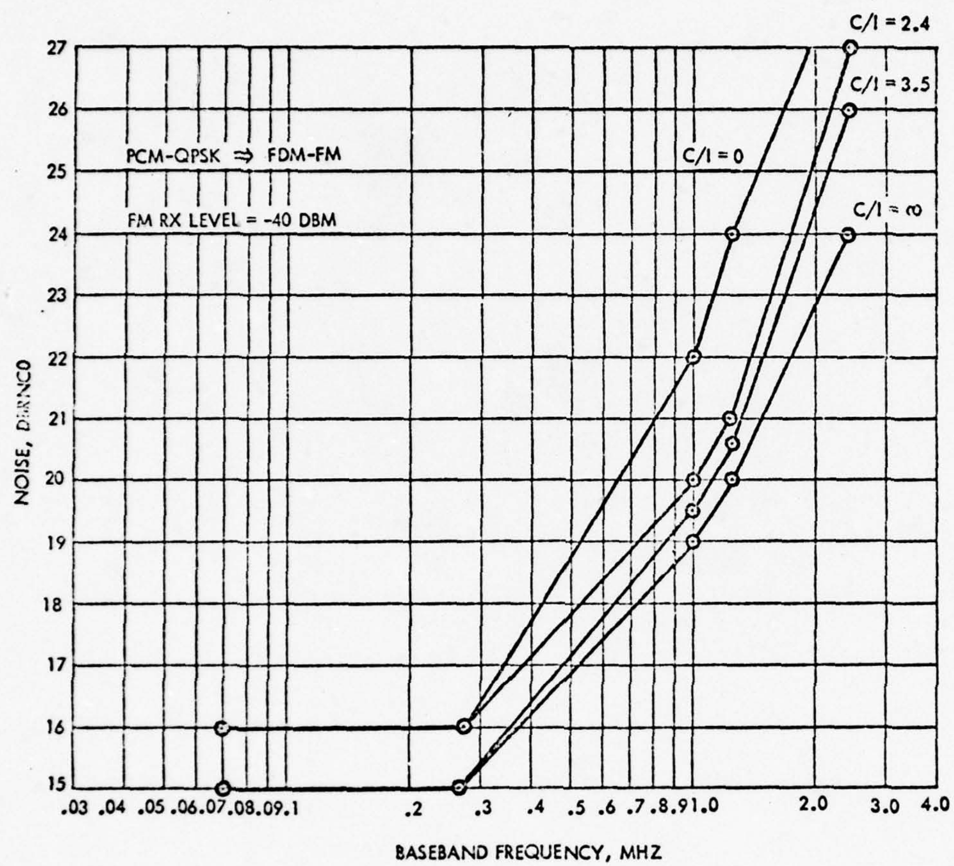


Figure 7-9. Adjacent Channel Interference Test Results.

(Source: Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System. Figure 7-5, p. 7-7.)

between digital and analog systems could not be utilized to provide interference protection for FM systems. Since most FM systems in commercial use were low power (1-10 mw), low capacity, FM short-haul, or high power (10 mw-1 w), high capacity, FM (1200 & 1800 channel) long-haul systems in the 6 and 11 GHz bands, the predominant problem was how to achieve sufficient containment of the RDS-80 emitted RF spectrum to prevent interference to existing analog systems and to future digital or analog systems. It was determined that severe RF filtering caused penalties in performance due to the reduction of receiver threshold.[14] Since this leads to necessarily shorter microwave paths, increased systems cost, and an increase in interference environment due to more emitters, a trade-off between no filtering and too much filtering of a digital signal can be inferred.

Conclusions

The work done by Raytheon for the New York Telephone Company answered many important questions which had previously been unanswered. Some of the more important broad conclusions and opinions reached were:

1) Out of band emissions can be filtered at the output of the RDS-80 digital transmitter to meet reasonable frequency coordination requirements with FDM-FM systems in the 11 GHz band.

2) The RDS-80 emission bandwidth was contained within the limits, which were established to control interference.

3) QPSK, that is four-level phase shift keying, provides a good trade-off between equipment complexity, emission bandwidth,

receiver threshold characteristics, and compatibility with cross polarization operation.

4) Cross polarization is a viable means of increasing the capacity of digital systems.

5) A solid state digital microwave system with a nominal output power of +30 dBm (1 Watt) can satisfy most systems' needs if a 40 dB fade margin is available on each link.

The Data Transmission Corporation (DATRAN) System

The Data Transmission Corporation (DATRAN) was founded in 1968 by Sam Wyly to compete with the world's largest telephone corporation, American Telephone & Telegraph Company (AT&T), in the transmission of digital data. Wyly's scheme initially was to develop a communications system that would transmit digital data from customer to customer; most such customers were computer-to-computer subscribers requiring high throughput rates, with an acceptable low error rate, and at a low cost. On the other hand, the AT&T system in 1968 was designed to carry the human voice in analog form, and was only marginally suitable for handling high speed data. Digital data could be sent only after it was processed through Digital to Analog converters (or modulators) and then it had to be decoded at the destination through Analog to Digital Converters (or demodulators), a slow and expensive process in the late 1960's.

The network as envisioned by DATRAN would consist of approximately 260 microwave relays deployed in a system extending from

San Francisco through Los Angeles to Dallas, Chicago, New York, and to Boston. The "All-Digital Traffic" would be controlled by a central computer switching system allowing terminals anywhere in the network to be instantly connected to other terminals in the network.

Finally in June 1971, over bitter opposition from AT&T, the FCC finally approved DATRAN's application[15] to enter the data transmission field. At this same time, DATRAN made a serious misjudgment in thinking that AT&T might continue to neglect the advancing digital transmission technology. As we have seen previously in this Chapter, Bell supported the Albany-Troy RDS-80 tests, and continued further testing in Pennsylvania. Reflections on the work appearing in various trade journals and the Bell System Technical Journal (BSTJ) clearly indicates a high level of Bell activity during late 1970 through the present. As if in response to DATRAN's thoughts, in October 1972 AT&T filed an application with the FCC to use some of the baseband spectrum just below the voice traffic carried by their microwave links for digital microwave transmission of data (Data-Under-Voice). The AT&T plan was to install digital multiplex units in its existing analog microwave network, thereby saving time and money. This was a less ambitious service offering compared to DATRAN's proposal, but perhaps it was more timely. The AT&T application was approved in June 1973 but without guidance on tariff structure. In previous Chapters, similar cases have shown that such applications usually take two to three years to process. It was thus

becoming apparent, that AT&T was out to compete fiercely with DATRAN,[16] and had already begun to lower rates on some of its analog lines which customers were using to transmit data as in the MCI System. When DATRAN completed the Houston-to-Dallas leg of its network, AT&T's price cuts forced DATRAN to lower its prices, thereby driving down the revenue which DATRAN had expected. However, at this time, DATRAN was technically ahead, and offered customers a digital transmission service that could carry higher rate data than AT&T, and cost about thirty percent less.

An often asked question was, why a separate communications service dedicated to the transmission of digital data? In short, the application of communications technology has not kept pace with the rapid developments in inter-computer and data service requirements.[17]

In order to compensate for that lag in communication's technology, and to meet projected FCC requirements (with respect to frequency stability and bandwidth occupancy), to meet construction schedules, and to stay within projected cost figures, it was necessary for DATRAN to use essentially off-the-shelf hardware. Since the domestic satellite system was not deployed at the time of the DATRAN initial system design, the choices were narrowed to the use of digital microwave radio and cable. Since accurate estimates of the costs to implement a cable system are difficult to make due to variation in installation costs and in the costs of obtaining easements, digital microwave radio was chosen as the means of

transmission. The digital signals would be transmitted distances in the order of 30-35 miles, and the digital signal would be regenerated at each repeater site, thereby removing any noise contributed by path perturbations and prohibiting noise accumulations. The system was designed for space diversity as opposed to frequency diversity, and did not incorporate any periscope or passive reflectors, since an effort was being made to control interference.

Instead of the usual 35-40 dB fade margin, a goal of 50dB was established and achieved in most cases. Hot standby transmitters were utilized as an order of redundancy. A bi-directional alarm system was utilized to ensure that alarm status information could still be recovered in the event of a link failure. Commercial power with standby power generation, and a battery reserve of eight hours, provided excellent power reliability.

The DATRAN System employed low-power transmitters operating in an output power range of 1 milliwatt to 10 milliwatts at 11 GHz, depending upon the required channel capacity and path length. Some high density, long haul paths required higher power levels. The use of low power radiation made it easier to meet the carrier-to-interference requirements of existing FDM-FM systems. Simultaneously, the highly tolerant nature of the digitally modulated signal permitted reasonable levels of interference from other FDM-FM systems without loss of performance. Through the discrete use of polarization discrimination and antenna radiation pattern

discrimination, the so called "two frequency plan" was utilized successfully in most cities. This plan employs the same frequency for all transmitters (or receivers) at a single site, thus allowing frequencies to be reused several times within a small area by alternately choosing vertical or horizontal polarization and antenna directional discrimination as necessary. An example of the successful application by DATRAN of these techniques was in Dallas, Texas, where the entire city microwave distribution system was engineered with only 11 radio frequencies.

In approaching their system design, DATRAN also investigated the potential use of frequencies in the 18 GHz and 39 GHz bands. They found that except for certain Military systems, no extensive application currently exists either commercially or militarily at these frequencies. Thus, to use these frequencies, there necessarily would be high development costs. High costs would be incurred for producing the requisite frequency sources, and the lower quantities of equipment that would be initially required would prohibit rapid amortization of the development costs. Further system's costs would be incurred due to the greatly reduced path lengths which must be used at the higher frequencies if the same degree of reliability is to be maintained. Rain attenuation of the signal becomes a more severe problem at higher frequencies. Due to these factors, it is estimated that the cost of an installed 18 GHz radio system would be twice the cost of an 11 GHz radio system; similarly, the cost of a 39 GHz radio system would no doubt be double the cost of the 18 GHz system. As discussed in Chapters Two

and Six, future technological advances can and will drive costs down in most cases. Until that happens, however, it would certainly be difficult to justify the construction of an 18 GHz or 39 GHz system.

Of interest was DATRAN's early conclusion that optical transmission was a valid interim technique to satisfy a customer's immediate requirement. In this manner a customer can be provided almost immediate temporary access into the system until permanent interconnect is accomplished through the use of low power microwave or cable. However, it should be borne in mind, that optical transmission is subject to complete interruption during conditions of heavy fog, snow, or rain.

Since this project is concerned with the treatment of microwave digital transmission, only a cursory look at the remainder of the DATRAN System is made.

The DATRAN customer interface device, which is analogous to the telephone instrument, is referred to as the Digital Control Console (DCC), as shown in Figure 7-10, The Datran Concept. The DCC connects the customer to the local distribution system, which is a composite of digital microwave radio, both baseband and multiplexed cable systems, and optical transmission devices.

A Time Division Multiplex Switching System, built by Comten Corp. and Stromberg Carlson, controls the microwave backbone trunks so as to make more efficient use of the circuits. By customers sharing the trunks, the circuits are utilized a higher percentage of the time, thereby

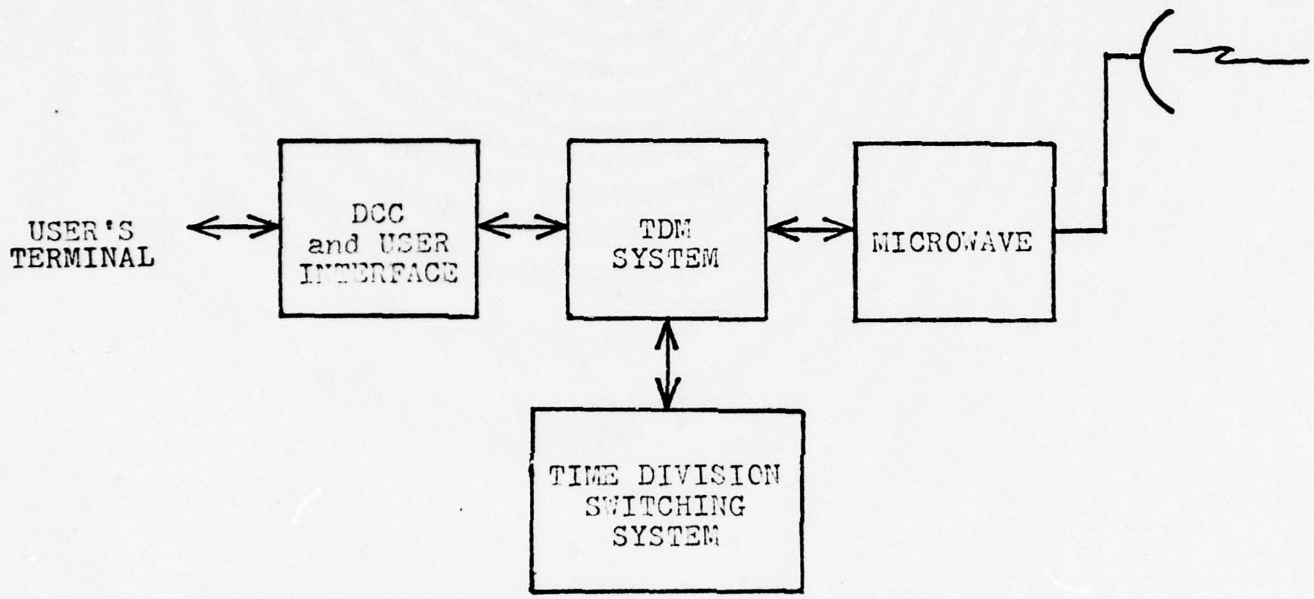


Figure 7-10. The DATRAN Concept

decreasing costs. The switching system provides low connect times, low percentage of blocking, abbreviated dialing, rotary, privacy, short minimum billing period (min. 6 sec.) and an out of service notifier feature.[18]

Of significant interest to the MILDEPS, was the DATRAN approach to maintenance. A fully digitized, full duplex orderwire allows any station to call either end of the designated maintenance section for assistance. The establishment of maintenance systems was predicated upon the requirement for rapid restoration of failed equipments, and the access time required to reach the stations. Since many of the stations were quite remote, a remote control capability was provided for the checkout of certain system functions. Maintenance aids were also provided to give maximum visibility of the system status so that fault isolation time would be minimized. Maintenance personnel were trained as experts on specific equipments, as is done in the Military through the various technical schools. The desired fault sensing capability was achieved through low cost drop and insert capability made possible by the previously mentioned digitized orderwire. Besides monitoring equipment status, the fault sensing equipment also monitored the status of the station facilities. All fault information is subsequently relayed to a central network status monitoring system for master control of the data network.

Why did such a well conceived and engineered system fall into bankruptcy? Was it ahead of its time? Some place the blame on heavy startup and operational costs—over $100 million—prior to generating any

revenue. Others say the service was limited; restricted to data only. Still others say that because of rising construction costs DATRAN had to rent leased lines from Bell which further depleted the capital.[19]

The Southern Pacific Communications Company (SPC) purchased DATRAN's \$58 M worth of book assets from the United States Bankruptcy Court for \$4.9 M.[20] SPC immediately combined the DATRAN digital transmission network with its own, and built a larger and improved central computer-controlled switch, and is now offering DATADIAL service to over 45 major cities. The new primary switch allows 10,000 separate connections in a non-blocking arrangement, and has a throughput capacity in excess of 75,000 calls per hour. Combined with the nation's only full duplex circuit switched data service (DATADIAL), is a new switched service designed primarily for voice (SPRINT). The new DATADIAL rates are currently about 25% under Wide Area Telephone Service (WATS).

In conclusion, DATRAN's concept may have been ahead of its time, as well as lacking the ability to provide multiple services. The systems engineering for that which was provided, was superb, but also superb, was Bell's stop gap, "Data Under Voice," and their subsequently developed digital system.

The FKV, A Quasi Digital Transmission System

The Requirement

In early 1972, increased emphasis was placed upon providing improved communications security in the Defense Communications System (DCS). Concurrently, it was becoming apparent to each of the MILDEPS that Operation and Maintenance (O&M) costs were soaring far beyond the pure inflationary factor. Therefore, for reasons of security, economy, and a desire to improve performance, the DCA had given considerable attention to the planning and engineering of a PCM/TDM system for a forthcoming DCS transmission upgrade. In early 1973, the Office of the Secretary of Defense (OSD) promulgated the following guidance to the DCA and the MILDEPS: "All transmission projects for Europe utilizing FY 74 and out-year funding, and where practicable, previously—approved projects with prior year funding, shall be implemented using multi-year, multi-option procurements based on a common family of digital equipment." In view of this guidance and the motivations for implementing digital transmission in the Military, a decision was made to satisfy the near term interim upgrade requirements with the most practical digital modulation technique available, so as to provide a reliable, yet maintainable system. Accordingly, the three-level partial response technique, as discussed in Chapter Three, was selected. Although the three-level partial response technique had a spectral efficiency of only about 0.9 bits per Hertz, as opposed to a 1 bit per Hertz spectral efficiency for QPSK, it had been

used successfully by commercial firms, and was field proven and rugged. In addition, suitable QPSK microwave transmission equipment was yet to be produced on a commercial basis.

The first Military application utilizing the three-level partial response technique was the Frankfurt-Koenigstuhl-Vaihingen (FKV) pilot digital communication system in the Federal Republic of Germany. The system is shown in Figure 7-11. Heidelberg is the northern terminus of the system, while Vaihingen near Stuttgart is at the southern end. The sites included in the system are Heidelberg (HDG), Schwetzingen (SWN), Koenigstuhl (KSL), Stocksberg (STB), Stuttgart (SGT), and Vaihingen (VHN). The link from Stocksberg to Koenigstuhl is 62 kilometers (38.5 miles) long while the link from Stuttgart to Stocksberg is 32 kilometers (19.89 miles); the remainder of the links are from 9 to 12 kilometers (5.6 to 7.5 miles) long.

The Technology/Problems

The decision to utilize three-level partial response was, of course, valid only if there was a viable radio which was economically adaptable to function with the three-level partial response equipment. In view of the testing performed, as discussed in Chapter Six, and the award of the DCS Microwave Radio contract to the Collins Radio Company, it seemed logical to modify the DCS Microwave Radio to accept the three-level partial response format. In previous discussion (Chapter Six), technical feasibility was proven by the Dept. of Commerce in January 1972, but accomplishment on

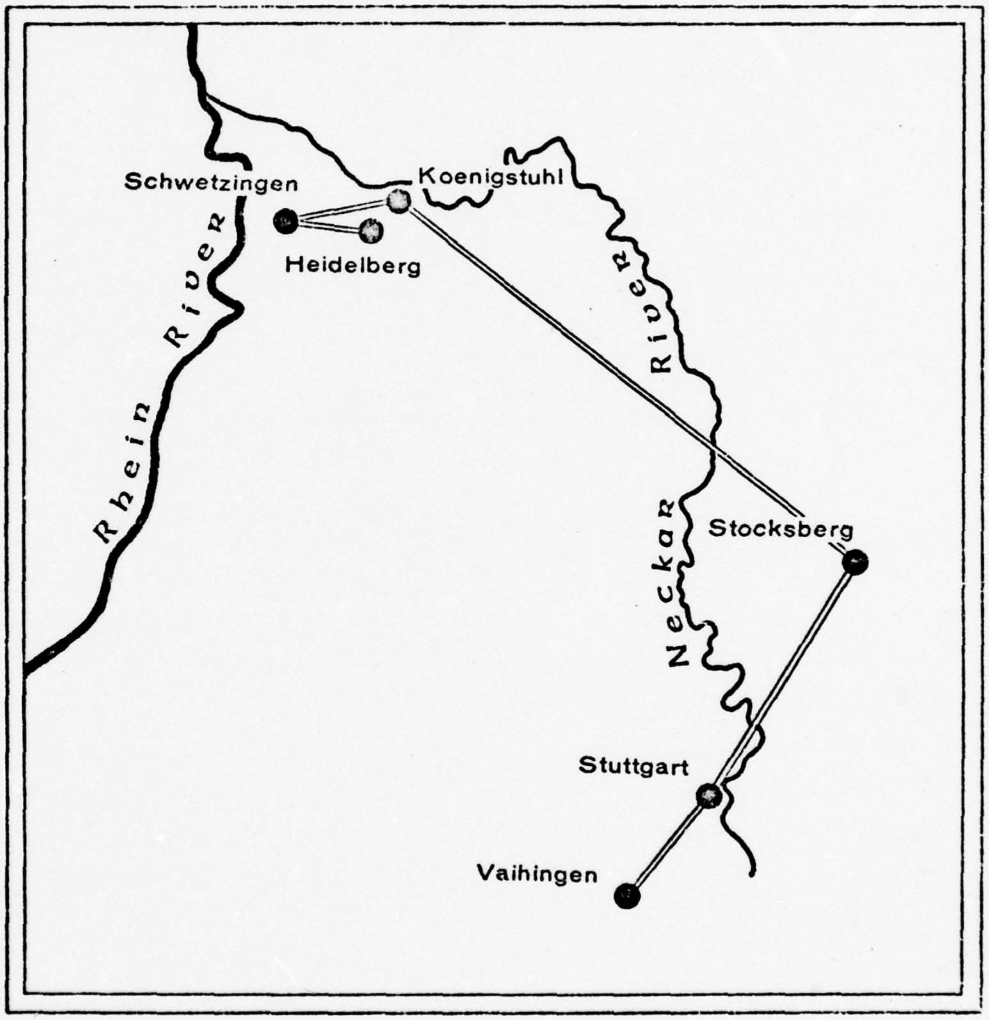


Figure 7-11. The FKV System

a production basis was yet to be performed. In this regard, a contract was awarded to the Collins Radio Company for determination of optimum operational parameters for PCM transmission over the DCS Microwave Radio. The work was performed under the direction of the Microwave/ Tropo Branch of HQ US Army Communications Engineering and Electronics Installation Agency (HQUSACEEIA). A fine cooperative engineering effort was put forth by Collins Radio in conjunction with VICOM, USACEEIA, OT/ITS, DCA, and DA technical personnel.

The specific objectives of the test were to determine:

1) Best performance configuration as a function of error rate
2) RF filtering requirements to include filter specifications
3) Cost impact to the DCS Microwave Radio considering modular additions or deletions.

The Collins DCS Microwave Radio Technical Proposal Verification Model (TPVM) was utilized in a back-to-back configuration to simulate one link. This radio was utilized in the competitive performance evaluation for the DCS Microwave Radio contract by the Department of Commerce, Office of Telecommunications, Institute of Telecommunications Sciences, at Boulder, Colorado in the fall of 1971. The radio is completely solid-state and is designed to operate in the 7.125 to 8.4 GHz frequency band. A minimum power output of +27 dBm (0.5 watts) is derived from a 2 GHz oscillator power amplifier and two sets of frequency doublers. The receiver contains a microstrip mixer and a solid-state local oscillator to produce a

70 MHz IF signal. The IF signal is demodulated to recover the baseband spectrum. Figure 7-12 illustrates the test setup utilized during these optimization tests. The transmitted baseband consisted of the digital multiplex and pilot connected directly to the transmitter modulation amplifier (J1). The FM and Single Sideband (SSB) Orderwire equipments were bridged directly onto a common baseband which was connected to the modulation amplifier (J2). The transceiver was aligned based on a per channel test tone level of 40 dBm into the modulator amplifier and 14 KHz rms deviation. The necessary receive levels were obtained by inserting a variable attenuator in the waveguide interface. The transceiver was operated at a frequency of 7.9 GHz with a 8.5 MHz pilot frequency. The orderwire information was impressed on a subcarrier which was located in frequency above the digital baseband.

Test measurements were made under varying conditions of deviation, receive signal level (RSL), and IF bandwidths. Additionally, both single sideband and frequency modulated orderwires were evaluated to determine their effect upon performance and quality of transmission when inserted above the PCM or digital baseband.

As a result of this test effort and the accrued data, it is possible to easily determine the best operational configurations and operational parameters based on implementation constraints and contractual requirements. The data contained in the Collins Optimization Test Report[21] allows selection of BER threshold, fade margin objective (with and

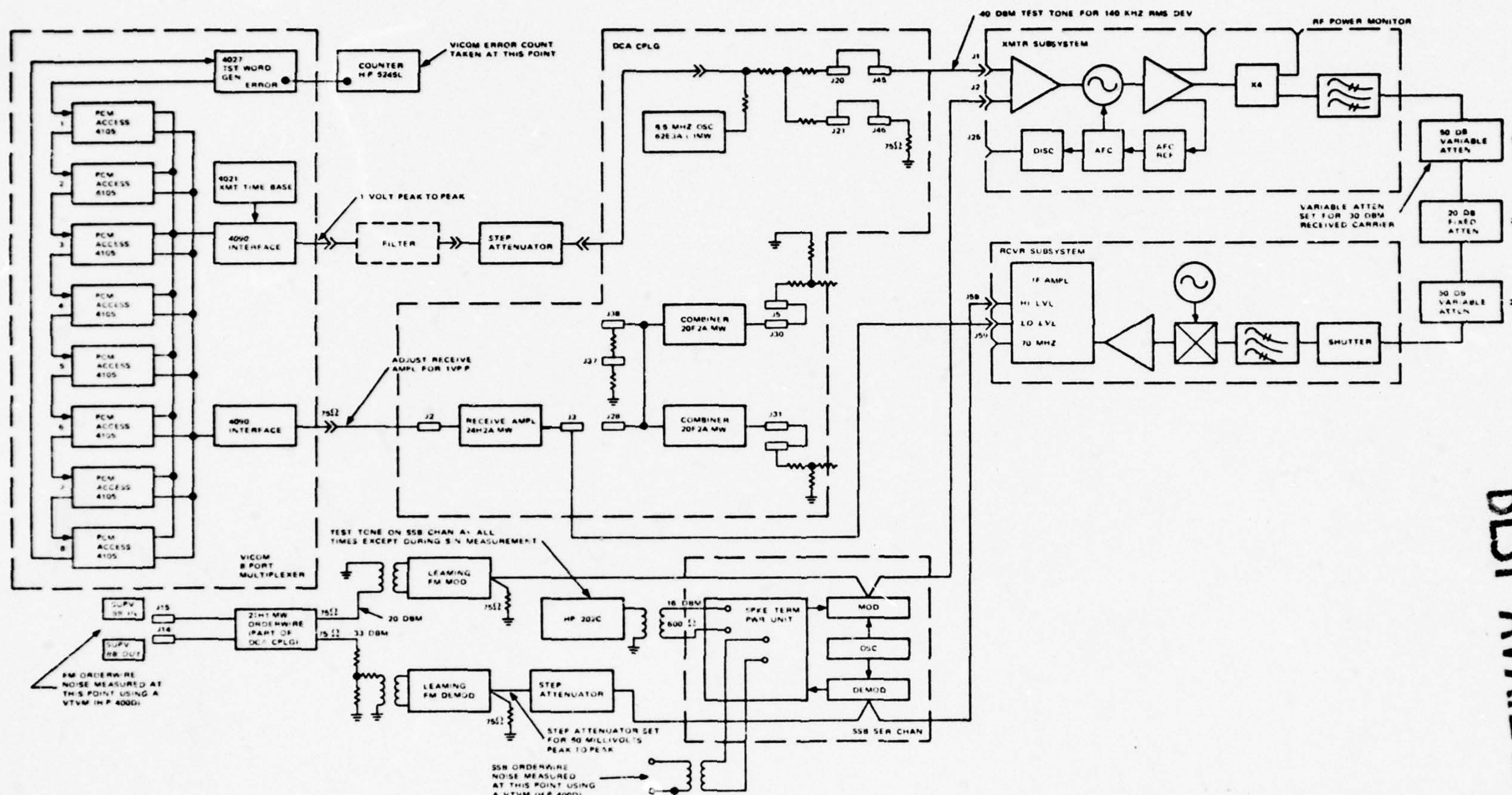


Figure 7-12. Test Setup for DCS M/W Radio Optimization Test for PCM Operation.

without orderwire), emission bandwidth information, orderwire signal-to-noise parameters, and baseband filter characterization.

During the testing period, questions were raised about which combining technique would provide the lowest technical risk for implementation in the FKV pilot digital communication system. As a result of these questions, additional tests, Appendix B, An Evaluation of the Baseband Diversity Switch Applied to Digital FM Operation,[22] were performed by the Microwave Tropo Branch of USACEEIA and the Institute of Telecommunications Sciences. It was determined that the most cost-effective, minimum technical risk approach to combining digital baseband data would be to use a baseband switch modified to achieve activation-deactivation about 5 to 6 dB above PCM threshold (corresponding to a received signal level of approximately -66 dBm).

Predicated upon the data from these tests and available system configuration information, a specification delineating the necessary modifications to the DCS Microwave Radio for PCM or digital performance in the FKV was prepared and negotiated with the radio manufacturer. In this instance, due to the technical risk, the government elected to furnish the radios to a system contractor, as opposed to having one contractor engineer, furnish, and install the entire system.

Implementation

A contract to Engineer and Install (E&I) the FKV system was awarded to the Raytheon Company in the last part of 1973 based upon use of the government supplied DCS Microwave Radio modified for digital transmission.

The FKV system was the first fixed point-to-point wideband communication system using pulse code modulation (PCM) of voice signals to be installed by any of the MILDEPS for use in the Defense Communication System.

The basic FKV transmission system as shown in Figure 7-13 consists of the previously discussed 8 GHz DCS Microwave Radio as modified for digital operation (AN/FRC-162), an 8-port time division multiplexer (T1-4000), and basic D-2 PCM channel banks.

In general, the multiplexer function is to time-interleave up to eight 1.5 Mbps data streams and, through filtering, provide a quasi-analog signal format suitable as a baseband signal input to modulate the FM radio. The spectrum of this baseband signal is uniform from approximately 300 Hz to 6.3 MHz and has a roll-off of 12 dB per octave up to 12.6 MHz. The uniformity of the spectrum is maintained through use of a scrambler on the output data stream to avoid the generation of significant spectral components that are caused by certain long runs of particular bit patterns. The D-2 PCM channel bank digitizes 24-4 KHz analog voice channels by sampling them 8000 times per second and by encoding each sample with an 8-bit code. This results in an equivalent rate of 64 kpbs per voice channel. These

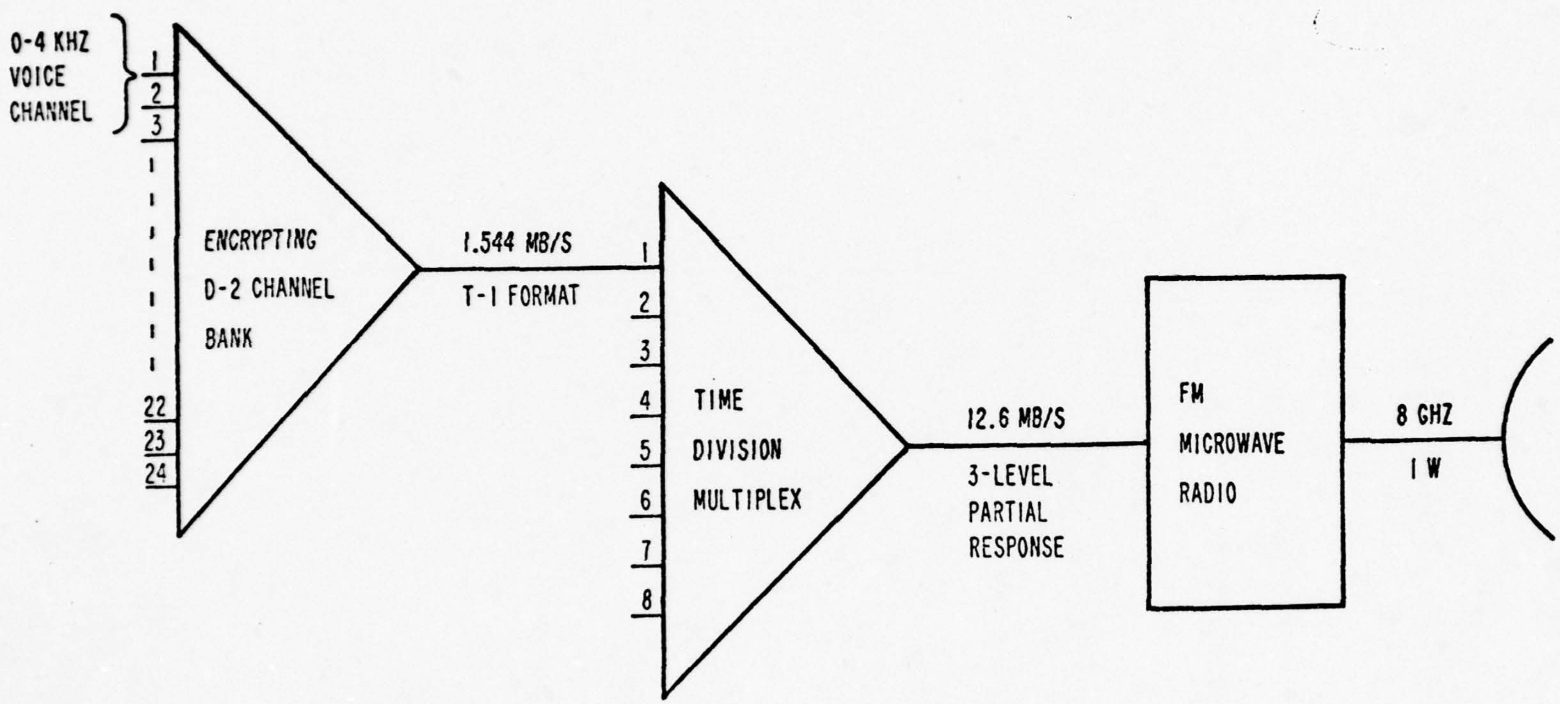


Figure 7-13. FKV Equipment Interconnection

digitized voice channels are time-multiplexed in the channel bank resulting in a 1.544 Mbps data output stream, often referred to as a T-1 bit stream. The total capacity of the system is then 192 voice channels. The 24 channels in a D-2 channel bank are commonly referred to as a digroup.[23]

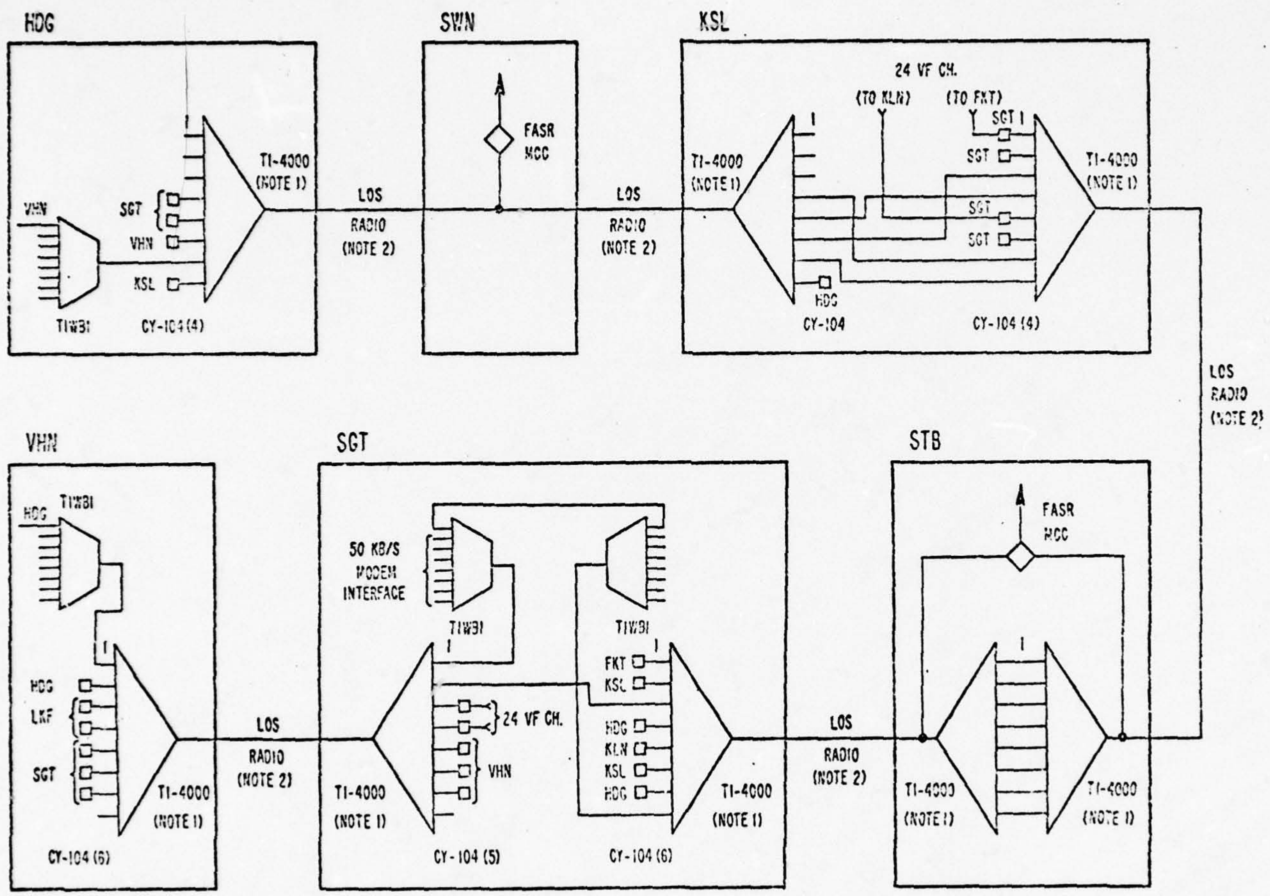
In discussing the D2 channel bank in more detail, it is pointed out that the transmit side of the channel bank is essentially an analog-to-digital converter, that is, the analog information signals (usually voice but also including data signals which have been converted to analog form through the use of modems) are sampled at a rate somewhat greater than twice the highest frequency. Subsequently, each sample is coded into a digital representation of the analog waveform. This digital code is sent to the receive side of the remote channel bank and converted by a digital-to-analog converter to its original analog waveform.

The channel bank used on the FKV system is called a D2 terminal but this is somewhat different from the Bell System D2 unit. The FKV D2 channel bank accepts 24 voice channels and samples each channel 8000 times per second. These amplitude samples are delivered to a common digitizer which converts each into an 8-bit amplitude code. These 8-bit codes known as channel words are combined into a 192-bit sequence which include one 8-bit code word from each of the 24 channels. One bit is added to this 192-bit sequence to provide frame synchronization; the resulting 193-bit sequence is a T1 line frame. The frame bits are sent in a 12-frame bit sequence (namely, "100011011100") and are identified as the framing signal and provide for synchronization of the channel signaling frames. The least

significant bit in every sixth channel frame is borrowed to carry the supervisory and signaling information. The rate of transmission for the 24 voice channels is 1.544 megabits per second (Mbps).[24]

The FKV system employs the VICOM T1-4000 Time Division Multiplex as shown in Figure 7-14, FKV Multiplex Plan. The T1-4000 time division multiplex unit accepts up to 8 asynchronous T1 bit streams and combines them into a single high-speed output stream. In order to successfully combine these eight T1 lines which are operating at slightly different frequencies, it is necessary to use some technique to make them synchronous. The technique used in the T1-4000 unit is bit stuffing. This technique adds dummy bits to each T1 stream to bring all eight up to the same frequency. The T1 streams in the T1-4000 multiplex output are brought up to a common rate of 1.544935 Mbps. Framing information bits, control information bits (which allows each T1 port at the receive side to match the corresponding one at the transmit side), and information recognition bits (which differentiate those bits that are T1 line data bits for the channel banks, from those that are stuffed dummy bits to be removed from the output) are all added together to bring the final transmission rate up to 12.552 Mbps.

The 12.6 Mbps non-return-to-zero (NRZ) signal is passed through a low-pass filter whose 3-dB response frequency is 4.5 MHz. This filtering of the 12.6 Mbps signal combined with the filtering done at the receiver input changes the NRZ binary data stream into a three-level partial response signal which requires only about half the bandwidth that the NRZ binary data



NOTES:

1. REDUNDANT MULTIPLEXER WITH PROTECT. SWITCHING.
2. DCSS 1-70(A) RADIO, SPACE DIVERSITY WITH PROTECT. SWITCHING.

Figure 7-14. FKV Multiplex Plan

stream would require for transmission. This is illustrated in Figure 7-15 which shows the waveforms various stages in the process of generating the signal to be transmitted to the different station.

Since failure of the multiplex unit at a station would interrupt all traffic through that station, the multiplex set was provided with one-for-one redundancy protection. The transmitters and receivers can switch separately and automatically from primary to standby but must be manually reset from standby to primary. For this reason, a rather complicated algorithm is used to activate the switch. The principal driving function is the inability of the primary multiplex to regain frame synchronization once it is lost. The sequence of switching is as follows. First, when the primary multiplex loses frame, the receiver switches to standby without latching. If synchronization is regained, the switchover is latched and operation continues. If synchronization is not regained, the primary multiplex is put back on line and the distant multiplex is signaled to temporarily switch to the standby transmitter. If this solves the problem, the transmitter switchover is latched. If the baseband is broken and the multiplex receiver cannot regain synchronism with any combination of receivers and transmitters (for instance, if the baseband signal is interrupted in one direction), the multiplex will continue to cycle.[25]

In concluding the discussion of the basic FKV transmission system, it should be noted that the AN/FRC-162 is configured as a hot standby transmitter with a dual space diversity receiver employing baseband diversity

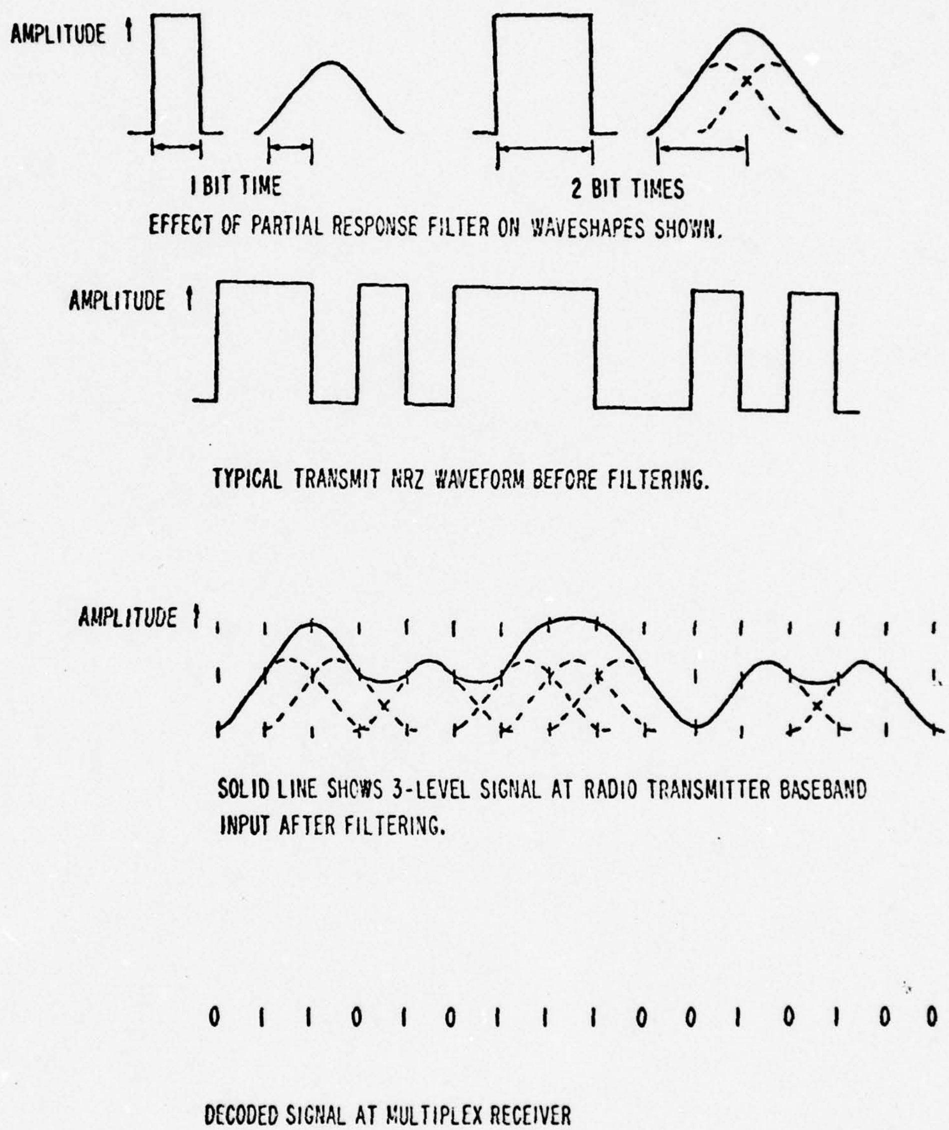


Figure 7-15. Partial Response Waveforms.

switching. The radio is a completely standard analog microwave radio, except for the fact that the level at which the baseband is injected is higher than that for an analog radio. Additionally, the radio is devoid of pre-emphasis and de-emphasis circuitry, and the orderwire is frequency modulated onto an 8.1 MHz subcarrier which is inserted into the broadened radio baseband.

Summary

Four distinctly different system approaches to solving user requirements have been examined: the first, MCI, used a pure analog approach which increased the use of the spectrum since this technique is inherently spectrally inefficient; the second, Albany-Troy RDS-80, used a completely digital radio employing QPSK and dual polarization for a claimed spectral efficiency comparable to analog; the third, DATRAN, used a total system concept employing switched digital trunking and digital radio; and fourth, the Military's FKV—a quasi digital transmission system—less spectrally efficient than analog voice transmission but capable of being implemented with commercially available hardware. Analysis of each of these system approaches shows that each occurred at a particular time during the digital evolution, were constrained by the available technology, and satisfied a particular user requirement. In the Military's case, it was shown that FDM-FM equipments would not permit bulk encryption nor would they accommodate the increasing number of digital users. However, even though engineering studies had indicated that the introduction of PCM, TDM, and

digital transmission into the DCS would not impair the overall DCS performance, it still remained to be proven in an actual system application.

CHAPTER 7

Footnotes

1. Don Mennie, "Communications and Microwave," IEEE Spectrum, (January 1975), p. 47.

2. Ibid., p. 47.

3. David R. Smith, "Performance Assessment of Digital Transmission Systems," National Telecommunications Conference, November 1973, Atlanta, Georgia, p. 4F-1.

4. Don Burnside, "The Pioneering MCI System," Microwave Systems News, August 1970, p. 12.

5. Federal Communications Commission, Docket No. 19311: Comments of the MCI Carriers, November 15, 1971, p. 1.

6. James Martin, Telecommunications and the Computer, 1976 Prentice-Hall, Inc., Englewood Cliffs, New Jersey, p. 32.

7. Communications News, $30 Million Program for MCI During Year, July 1977, p. 3.

8. Raytheon Data Systems, Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System, Norwood, Massachusetts, (April 5, 1973), p. 1-1.

9. Ibid., p. 2-1.

10. Ibid., p. 4-1.

11. Ibid., p. 4-4.

12. Ibid., p. 4-11 and 4-12.

13. Ibid., p. 7-6.

14. Ibid., p. 7-21.

15. Bylinsky, Gene, "DATRAN's Hazardous High Wire Act." Fortune, (February 1976), p. 132.

16. Ibid., p. 134.

17. Allen R. Worley, The DATRAN System, Proceedings of the IEEE, November 1972, Vol. 60, No. 11, p. 1357.

18. Ibid., p. 1365.

19. Bylinsky, op. cit., p. 139.

20. "SP Communication's Gus Grant and Rex Hollis Talk About DATRAN." Communications News, July 1977, p. 26.

21. Collins Radio Company, Transmission of Pulse Code Modulation on DCS Microwave Radio, Optimization Test, 10 September 1973, p. A1-C52.

22. Richard E. Skerjanec, An Evaluation of the Baseband Diversity Switch Applied to Digital-FM Operation, Letter Report to USACC, March, 1973.

23. R.E. Skerjanec, J.E. Farrow, FKV Pilot Digital System Evaluation, OTM 77-238, Institute of Telecommunications Sciences, Vol. I, July 1977, p. v.

24. Ibid., Vol. III, July 1977, p. 4.

25. Ibid., p. 5.

CHAPTER 8

ANALYSIS AND CONCLUSIONS

Many communication systems have been engineered, manufactured, and installed, but have failed to meet the stated overall performance criteria. Usually this occurs when numerous new equipments are interfaced together on a systems basis for the first time. Sometimes such problems can be avoided, time permitting, if the new equipments are interfaced in a systems test bed prior to installation. However, in some instances time and costs are overriding factors and the onsite installation must proceed. In either case, confirmation that the system design is indeed correct and that each of the established and desired performance parameters are being met or exceeded is still required. Without confirmation of this, the equipment engineer, system engineer, installer, and operator will never recognize or be able to correct design, engineering, installation, or operator errors. In fact, if a problem was found but not reported, that same problem may be repeated on the next equipment or system design. This situation is particularly likely to occur when a new or emerging technology is used, and where there is little existing definitive information or test data. Since the FKV system was indeed using new and relatively untried equipment, it was decided to perform a comprehensive analysis

with respect not only to technical parameters, but also with respect to the operational aspects including the level of manning, quantities of spares, test equipment, logistic support, and the quality of documentation. Such information could be readily used to improve future engineering, installation, and operation of similar systems.

Frankfurt-Koenigstuhl-Vaihingen (FKV) Analysis

In the spring of 1974, the U.S. Army Communications Command requested that the Institute of Telecommunications Sciences (ITS) perform a comprehensive performance evaluation of the FKV pilot digital communication system. The purpose of the evaluation was two-fold; first, to collect and analyze performance data to verify the adequacy of the FKV digital transmission system design (this analysis was to treat, as a minimum, the microwave path design, equipment configuration, system peculiar technical effects, and the adequacy of station, link, and system acceptance tests); and second, to evaluate the adequacy of personnel training, of current maintenance concepts, of test, maintenance, and diagnostic equipment (TMDE), of equipment redundancy, of station equipment layout, and of human engineering factors. This project will only treat the first purpose stated above, that is, the adequacy of the FKV digital transmission system design.

The transmission system technique used for the FKV system is described in Chapter Seven, Digital Transmission Systems under the FKV: "A Quasi Digital Transmission System."

Evaluation Data Collection System

The Institute of Telecommunications Sciences (ITS) designed and built minicomputer-based acquisition terminals at Heidelberg, Koenigstuhl, Stuttgart, and Vaihingen. A central minicomputer was located at Heidelberg while satellite computers were located at the remaining named sites. The data acquisition equipment was connected to approximately 70 test points per terminal end. The test points consisted of built-in-alarms, special functions not normally alarmed, and various analog parameters such as received signal level (RSL), voice channel noise level, and test tone stability. The information from the various test points was collected by computer controlled peripheral equipment such as frequency counters, pulse totalizers, analog to digital converters, 16-bit transistor-transistor logic (TTL) change of state detectors, and hardware interrupters. The data were recorded on magnetic tape and sent to the ITS facility at Boulder, Colorado for further data reduction and analysis by computer. To complement the automatic data collection, observations and interviews were made by an ITS resident engineer. These observations and interviews addressed the less quantifiable areas such as adequacy of training, understanding of system concepts, ability to maintain the communication system, and the degree to which human engineering factors were considered in system design.[1]

Radio Propagation and Prediction

Various radio propagation prediction models have been developed to make estimates of the propagation effects on planned microwave radio links.

In the past, the most frequently used model was that described in the National Bureau of Standards Technical Note 101. This model provides long term estimates of distribution of the hourly median values of transmission loss without attempting to describe what happens within any hour.

In perspective of the new digital systems, a better approach appears to be the model developed by W. T. Barnett of the Bell Telephone Labs in 1972 and expanded by A. Vigants[2] (1975), also of the Bell Telephone Labs. The Vigants model permits an estimate to be made of the total time within heavy fading periods during which the transmission loss will exceed the long term median loss by various margins. This information is significant for analog systems but it is critical in the design of digital systems.

The Vigants model (as does the T.N. 101 method) contains factors for various types of climate and terrain, path distances, and carrier frequencies. The use of the Vigants approach to predicting the performance of line-of-sight radio links is being encouraged by the DCA in the Defense Communications Engineering Center Technical Report No. 12-76 titled "DCS Digital Transmission System Performance," and is being considered for inclusion in the CCIR official publications.

Comparison of the predicted and measured receive signal level, utilizing the Vigants technique, for the longest link of the FKV System is depicted in Figure 8-1, Comparison of Predicted and Measured RSL. The dashed line through the stars is the calculated long-term median value and an estimate of the lower limit of received signal level for the worst fading period (nominally one month). It can be seen that this particular prediction model considerably overestimates the fraction of time that reduced signal levels would be expected.

It is interesting to note that neither of the models (NBS Tech Note 101 or the Vigant's model) attempt to predict rain attenuation, yet the only known instance of propagation outage[3] on the FKV was a twelve minute period during the evening of 17 July 1976. An intense rain storm (7.1 in/hr) caused the receive signal level to decrease to -65 dBm on the Heidelberg-Schwetzingen and Schwetzingen-Koenigstuhl links. Both diversity branches of each link were affected equally. An interesting aspect of this situation is that neither of the two radio links exceed ten miles in length, and yet the increase in attenuation over each path from the intense rain was greater than 36 dB.

System Performance Assessment

The engineering of a communication system is an exceedingly complex process drawing on many different engineering disciplines. The quality of the service provided is directly dependent upon the adequacy of each part of the system, to include all of the human and physical assets necessary to provide the desired user services.

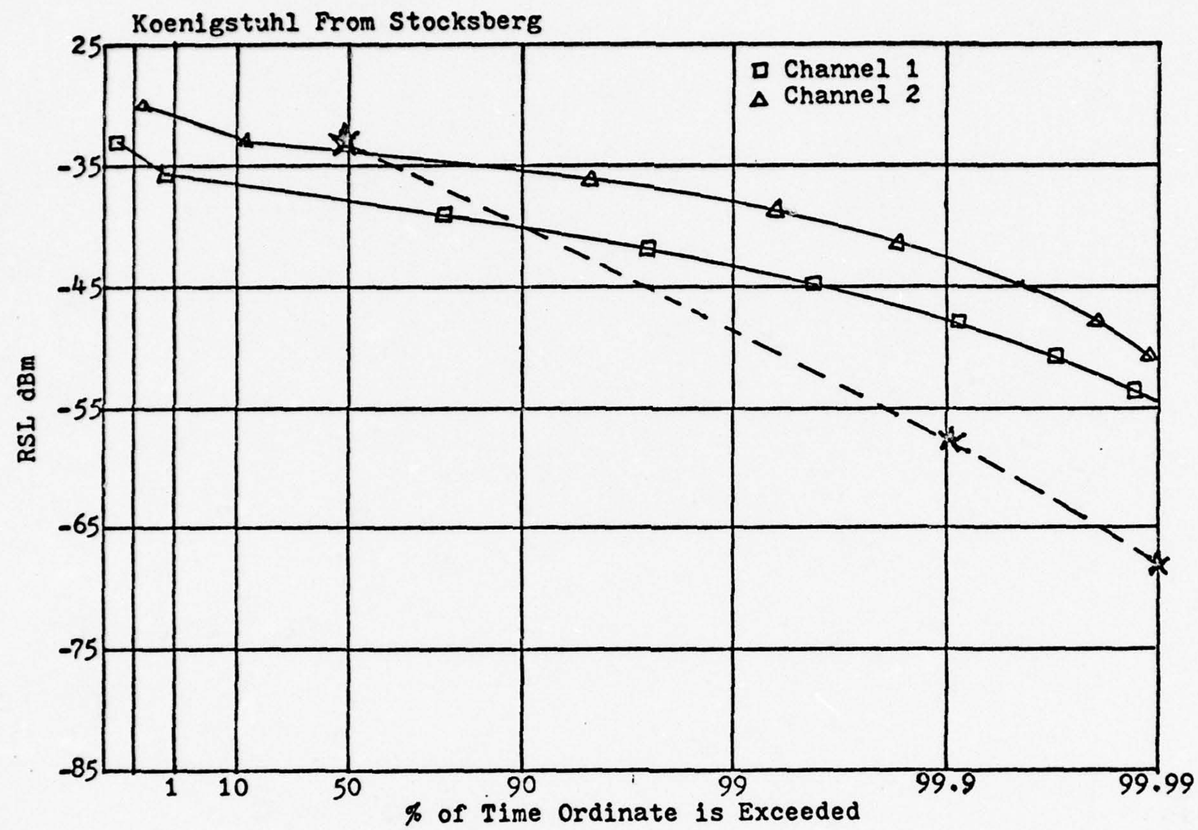


Figure 8-1. Comparison of Predicted and Measured RSL.

(Source: FKV Pilot Digital System Evaluation Final Report, July 1977, Vol. III, p. 12, Figure 3.1-4.)

In general, the FKV Pilot Digital System Evaluation has found that the FKV-type digital microwave system can form an acceptable part of the DCS. Technically, the system design was found to be acceptable. As a result of the design criteria utilized, no system outage, excluding the power system, was observed in those major subsystems protected by a redundant element.

In spite of meeting most of the technical performance criteria, there is a need for improving system test and acceptance procedures, improving operating procedures, and developing a fault isolation algorithm to facilitate rapid system restoral in the event of a failure.

Initial results from the evaluation indicate that there is no clear cut set of trending parameters for use in early detection of incipient system failure.

A brief overview of the technical results indicates that, for instance, the multiplex frame error burst size is usually very small (about two thirds of the bursts consisted of 1 to 3 events) and the mean time between such bursts is about nine hours. Similar mean times were observed between voice channel test tone changes.

An important engineering consideration in making a site layout concerns the interconnection between the highest level multiplex and the radio. In particular, the required length of the RF transmission line (generally waveguide) within the building and the required length of baseband coaxial cabling to connect the radio to the highest-level digital multiplex is of prime concern. The principal considerations for the waveguide are

the loss of signal through the waveguide, the dollar cost of the waveguide, and the difficulty of installation. For the baseband coaxial cable, consideration must be given to degradation of the digital signal in the cable and noise pickup, both of which increase as the cable length increases. In general, these situations occur because the format of the digital signal, that is the three-level partial response signal (which is used for transmission in the FKV system), was designed to be compatible with an FM radio baseband. This means that low frequency components are present in its spectrum, and the signal is shaped with a low-pass filter. Both of these conditions make such a signal ideal as an FM radio baseband, but the worst possible signal for transmission through a coaxial cable. The reasons for the coaxial cable problems are first, that the ratio between the upper and lower 3 dB points of the spectrum is too large, i.e., $\frac{6,300,000}{400} \approx 16,000$; and second, the effective shielding provided by the coaxial outer conductor decreases rapidly with frequency, and becomes negligible below a few kilohertz. The problem with the wide spread in frequency is that the pulse distortion caused by the non-uniform attenuation versus frequency characteristic of the cable is more severe than for a signal of equal bandwidth with a higher center or average frequency. The second effect means that low frequency interfering signals and noise can easily enter the cable and degrade the digital signal with additive noise.[4] The best way to reduce both of these noise sources is to shorten the length of 12.6 Mbps digital baseband cable as much as possible by careful radio-room layout.

In contrast to the 3-level baseband signal, the T1 line signal is in a 1.544 Mbps bipolar AMI (alternate mark inversion) format which was chosen for its suitability to being carried by cable. This is because it has reduced low-frequency components and any low-frequency noise can be filtered from the signal. Furthermore, its lowest and highest frequencies of concern have a fairly low ratio so the problem of distortion is lessened. In addition, it is usually carried on cables which are balanced to ground so that a twisted pair or a similar type of cable will give considerable reduction of low-frequency coupled interference.[5]

Since some of the FKV sites had long baseband coaxial cable runs and faults in the cable were found, the recommendation was made to place the multiplex racks directly adjacent to the radio rack in the future. Additionally, deficiences were found in the fabrication of cable terminations and in the installation and tying down of the high-speed digital coaxial cable. Tests of the cable runs should be conducted to insure that the cable installation will introduce minimal pulse distortion.

A propagation outage of 12 minutes was experienced due to intense rainfall as discussed earlier in this chapter. It is important to note that this was experienced even though the measured Median RSL and Fade Margins met the predicted values within reasonable limits, as shown in Table 8-1.

Greater detail may be obtained in the FKV Pilot Digital System Evaluation, FKV Report OTM 77-238, Vol. III, Engineering Analysis.

TABLE 8-1

FKV SYSTEM RECEIVED SIGNAL LEVELS

Path	Path Length	Predicted Median RSL	Predicted Fade Margin	Measured Median RSL	Measured Fade Margin
Heidelberg-Schwetzingen	9.3 km	-29 dBm	41 dB	-29 dBm	41 dB
Schwetzingen-Koenigstuhl	12.1 km	-30 dBm	39 dB	-33 dBm	37 dB
Koenigstuhl-Stocksberg	62.2 km	-33 dBm	38 dB	-33 dBm	38 dB
Stocksberg-Stuttgart	31.8 km	-30 dBm	41 dB	-35 dBm	36 dB
Stuttgart-Vaihingen	12.5 km	-28 dBm	43 dB	-35 dBm	36 dB

A more direct measure of the system performance is the system availability. The FKV Pilot Digital System Evaluation as performed by ITS during a year long evaluation indicates a measured value of digroup unavailability of 2,040 minutes. The FKV system contractor had predicted a circuit unavailability of 12.3 minutes per year, while the Defense Communications Engineering Center had predicted 52.6 minutes per year.

This large disparity results not only from the engineering aspects of the system, but such things as operational and maintenance practices as well. In the FKV evaluation, the measured value of unavailability is the mean cumulative outage time for the 26 CY-104's in the system. The measured outage represents the period during which at least 24 channels were unavailable for use. The outage time of 2,040 minutes is comprised of the following causes:[6]

Cause	Cumulative Minutes of Outage
Propagation	12
Key Changes	50
Equipment Failure	180
Prime Power Failure	520
Human Error	1,278
Total	2,040

It is interesting to note that under the categories of Equipment Failure and Human Error a close interrelationship exists. There were extended periods during which system performance was affected by equipment failure compounded by human error. Examples of this were, the

manual switching of the radio baseband output by the system operators from the operating diversity branch of the radio to the failed branch of the radio, extended periods of intermittent CY-104 operation following key changes, extended outages following installation of equipment, inadequate system fault isolation procedures, and the unavailability or the inoperability of spare modules.[7] It is important to realize, that even though the periods of time involved in solving each of these problems were usually relatively short, their cumulative total rapidly becomes large and is therefore, the dominant contributor to system outage time.

As discussed in Chapter Seven, in the Data Transmission *Corporation (DATRAN) System section*, the Operations and Maintenance concept of a system is of extreme importance to successful system performance. DATRAN, as previously pointed out, invested heavily in this area for their backbone systems, but was unable to capitalize on the investment due to their inability to control their leased extensions. Since operation of a military system is primarily concerned with the quality of service, and the time availability of that quality of service to provide critical military communications in support of a military mission, all operational concepts and practices should be in support of that objective. In this regard, the FKV system appeared to be deficient, as an operational concept did not exist.[8] A suggested list of some important operational practices was developed during the evaluation and is contained as Appendix C.

The outage due to prime power failure is obviously large; however, it will not be treated in any detail in this project. Prime power sources on almost all DCS sites have been built with multiple redundancy so that a station failure due to loss of power is expected to be so rare as to have a negligible effect on the total system availability. The reasons this was not true with regard to the FKV system are discussed in detail in FKV Report OTM 77-238, Volume III, Engineering Analysis.

With further respect to operational performance, performance parameter measurements are currently being made and recorded to indicate system trends. The parameters reported on DCS FDM systems are RSL, baseband loading, and idle channel noise. On the FKV system, RSL is still of importance, but baseband loading is constant and need not be monitored. Additionally, idle channel noise on a VF channel may not be as sensitive an indicator of system quality as it had been for FDM-FM systems. A more useful parameter would be test tone hits (either increases in level or dropouts) derived from a dedicated or time-shared channel.

<u>Summary</u>

In summary, it was found that the voice channels carried by this pilot digital transmission system are subjectively much quieter than those previously available on the FDM-FM system. The data users found that their net throughput was larger due to fewer data blocks requiring retransmission because of greatly improved error rate performance. It appears

that the basic structure of the three-level partial response digital technique is sound enough to survive most system perturbations, and is further able to recover from a total loss of baseband signal. Thus it can be said with confidence that, with respect to the digital transmission technology employed, the FKV pilot digital transmission system has proven to be an unqualified success and a major step toward the "all digital DCS."

Frequency Congestion and Its Impacts

Frequency congestion, spectrum utilization, and mutual interference have been and will continue to be major problems facing all providers of telecommunication services. The Military is no exception.

Regulatory action by the FCC, as a result of FCC Docket 19311,[9] has placed a requirement as to the minimum number of digital voice channels that must be handled within each of the commercial microwave bands below 15 GHz. Consequently, spectral efficiencies of two to four bits per Hertz are required. This, coupled with the wider bandwidth requirements of the higher data rates, has forced the design engineers to use higher order modulation techniques.

This is reflected in the Military's specifications for the Digital Radio and Multiplex Acquisition (DRAMA) equipments. The DRAMA hardware will be utilized for planned upgrades in the DCS as discussed later in this chapter.

The use of the more complicated modulation techniques alone is not enough to cope with the rapidly increasing demand for new and expanded

digital services. Another partial solution[10] lies in the assignment of frequencies within the 15, 18, 22, and 38 GHz bands that have been established within the International Radio Regulations. The use of these frequencies, however, is subject to the limitations imposed by the transmission medium. These include attenuation and scattering by atmospheric gases, hydrometeors such as rain, snow, hail, and clouds, and irregularities in the refractive index of the lower atmosphere structure.

It must be anticipated that the host countries will want to recover and use the lower frequency microwave bands for their own civil and military use. This would preclude any expanded U.S. Military use of these bands. Thus any further U.S. Military expansion must be accommodated in the higher frequency bands. This was shown by the necessity to move the DCS radio link frequencies used in Germany from 2 to 8 GHz.

Mutual interference problems between analog transmission systems, digital transmission systems, and satellite transmission systems that operate in shared or adjacent frequency bands have placed increased emphasis upon the need for a highly professional Frequency Management Program on both the national and international level.

FCC inquiries and subsequent FCC rulings have provided the "FCC mask" at the national level to serve as a standard for controlling occupied bandwidth and out-of-band emissions of the digital power spectrum. This had an impact on the equipment manufacturers as none of the digital radios tested by the Military under DTEP were built to meet the final out-of-band emission standards established by the "FCC mask" for digital microwave

use. As a consequence, all manufacturers of microwave equipment are now required to turn to expensive and complex RF filter technology to comply with the FCC requirements.

Internationally, the ITU has recognized that digital and analog systems can coexist without large penalties in spectrum utilization,[11] and has organized study programs to investigate RF channel assignments for use in the 10.7 to 11.7 GHz and the 17.7 to 19.7 GHz frequency bands. Results of these investigations should be available after the next Plenary Assembly which is to meet in Geneva, Switzerland in early 1978.

Future Digital Systems

The DCA Plan for communications through the early 1980's reflects a primary transition from analog to digital transmission. This transition will include all DCS subsystems from satellite to packet switched subsystems. As highlighted in preceding chapters, digital transmission within the DCS promises improved communication security, flexibility for accommodating an increased number of new digital users, and will provide for direct interoperation with digital tactical communications. The DCS will be required to carry an increasing digital traffic as discussed in the ten year requirements projection of data and secure voice traffic beginning in 1978.[12] These requirements will be satisfied primarily with the introduction of AUTODIN II, and Phase Two Secure Voice programs.

It is expected that within the overseas DCS, the growth of digital transmission will be rapid. Defense policy dictates that all significant

communications upgrades and extensions of DCS facilities will be implemented using digital transmission technologies.

The main driving force for improving the Military's digital transmission capability within the DCS is the Phase Two Secure Voice Program.[13] Recent developments in digital technologies by industry and government have provided the capability to design the necessary hardware for all digital transmission in the DCS.

Impact of Technology

A look into the future of communications technology reveals that the pace of technological innovation is accelerating rapidly and the Military is accordingly challenged to monitor and keep abreast of these technologies for possible application within the DCS. Important progress has been made in the digital radio market as is exhibited by Raytheon's digital radio. It utilizes 8-PSK modulation and transmits 89 Mbps within a 40 MHz emission bandwidth, without the use of cross polarization. Collins has also developed a radio with similar capabilities.[14] These are important developments since increased channel capacities and efficient spectrum utilization will continue to be a primary concern in the design of digital microwave transmission systems.[15] Raytheon's Eight Phase Shift Keying and raised cosine filtering[16,17] can provide 3 bits per Hertz of spectral efficiency with a minimum amount of interference to existing analog and digital systems. Interference prevention is essential in a channelized radio environment, especially when an FDM-FM system is within the range of influence of a

digital transmission system. For future applications at higher spectral efficiencies, IF and RF modem design must be adaptable to perform at 6 or 8 bits per Hertz. To achieve this level of efficiency, Single Sideband Quadrature Amplitude Modulation (SSB-QAM) utilizing cross polarization[18] must be considered.

New software methodology combined with new modulation techniques, as mentioned in the history of PCM, are the basis of achieving the higher usable spectral efficiencies. Modulation and coding techniques are complimentary in operation in that both act to make the communication system more efficient. For example, Continuous Variable Slope Delta Modulation (CVSD) is capable of reducing a per-voice-channel requirement of 64 Kilobits per second (kbps) of data down to 16 kbps, which could provide a reduction of four to one in required emission bandwidth.

Integrated circuits benefiting from LSI, MSI, and MOS technologies are being incorporated into systems and subsystems thereby providing a cost-effective advantage for the digital transition. Power Gallium Arsenide (GaAs) Field Effect Transistors (FET) are providing much needed power sources for the microwave frequencies. GaAs FET amplifiers are now replacing the TWT, tunnel diode, and parametric amplifier in low noise applications up to 18 GHz. Developments in sub-millimeter waves and integrated optics, together with improvements in signal processing, will permit the use of higher frequencies.

The component technologies discussed above have made possible the cost effective marriage of computer systems and communications systems

into computer-communications[19] systems which when applied to satellite communications improve their data and voice handling capability and efficiency. These facts coupled with the increased transmission reliability of satellites have lowered the cost of long distance communications while increasing satellite traffic handling capability. Concurrently, the Defense Satellite Communication System (DSCS) is in the process of converting to digital transmission. The DSCS provides a vital link with the United States and NATO countries for coordination of Command and Control functions. Further developments in satellite multibeam antennas provide simultaneous operation over both 4 and 6 GHz frequency bands, and with sufficiently low sidelobes such that 27 dB of isolation can be achieved between a set of six simultaneous dual-polarized beams. Using optimum beam positioning, 80 percent of the earth's disc can be covered, and if satellite rotation is possible, the composite coverage can be 97 percent of the earth's surface visible to the satellite. These increases in bulk transmission capacity are sure to require increased terrestrial, line-of-sight distribution capability.

A world-wide, three-dimensional, navigation positioning system, NAVSTAR, is under development by the Military which will incorporate twenty-four satellites using QPSK modulation. The NAVSTAR Global Positioning System will provide continuous navigation assistance to anyone with the proper receiving equipment; from the soldier in the field to the strategic forces of missiles, submarines, and aircraft.

An important capability to government agencies is the transmission and reception of classified information in hard copy. In this endeavor,

DACOM Incorporated has successfully tested for the government a secure facsimile. It is compatible with AUTODIN, and provides total security during transmission of security sensitive information.

Within the total DCS, facilities and equipment will be required to provide wideband digitized voice, secure voice, digitized TV, facsimile, and high speed computer-to-computer interface.

Digital Radio and Multiplex Acquisition

As a result of abundant digital technology application, the Military has introduced a new family of digital equipment under the Digital Radio and Multiplex Acquisition program (DRAMA). This program, with an initial purchase *contract for $30 million*, provides the standards and specifications for the digital radio and multiplex to be used in future Military upgrades. The DRAMA equipment includes the AN/FRC-163 Digital Radio, the TD-1192 First Level Multiplex, and the TD-1193 Second Level Multiplex.

The An/FRC-163 Digital Radio operates in the 4 or 8 GHz government bands and employs either space or frequency diversity. Additional characteristics are hot-standby configurations, automatic and manual switchover, hitless diversity switching, Mission Bit Stream rates from 3 to 26 Mbps, and built-in performance monitors of frame errors, RSL, and signal quality.

The TD 1193 Second Level Multiplex (TDM), is an 8 port device with a combined output rate of 12.9 Mbps. Salient characteristics include full redundancy with automatic switchover, synchronous or asynchronous operation, built-in performance monitor using frame errors, and a capability to control the KG-81 encrypting synchronization.

The initial use of this equipment will be in the Digital European Backbone Phase II Upgrade. Figure 8-2 titled Comparison of FKV/DEB Stage I vs. DRAMA, illustrates some of the differences between the system approaches used for the FKV/DEB I systems and the DRAMA systems.

<u>DCS Digital Microwave Transmission Upgrades</u>

Today, the DCS consists of more than 700 microwave communications links. During the next decade, the Military has planned to upgrade over 230 microwave links to digital transmission in order to achieve an all digital DCS. Approximately 100 of these links are in the Pacific theater, while approximately 130 are in the European theater. Additional commercial leases are planned for Trans-Atlantic and Trans-Pacific services. The European digital upgrades include the Digital European Backbone Phase I-IV, (DEB I, DEB II, DEB III, DEB IV), and other upgrades in Turkey, and Greece. The interim solution as utilized in the FKV system will also be utilized for DEB I, constituting approximately 17 interim links (combined). Other near-term European Wideband Communications System upgrades will account for an additional 12-18 links for a total of 35. The DRAMA equipments will be the DCS standard for all upgrades subsequent to DEB I.

The Digital European Backbone (DEB)[20] Terrestrial Transmission Upgrade Project is a joint effort of the USA, USAF, USN, DCA, and NSA. Its purpose is to provide secure and stable communications for the Department of Defense and its European subscribers. The DEB project will

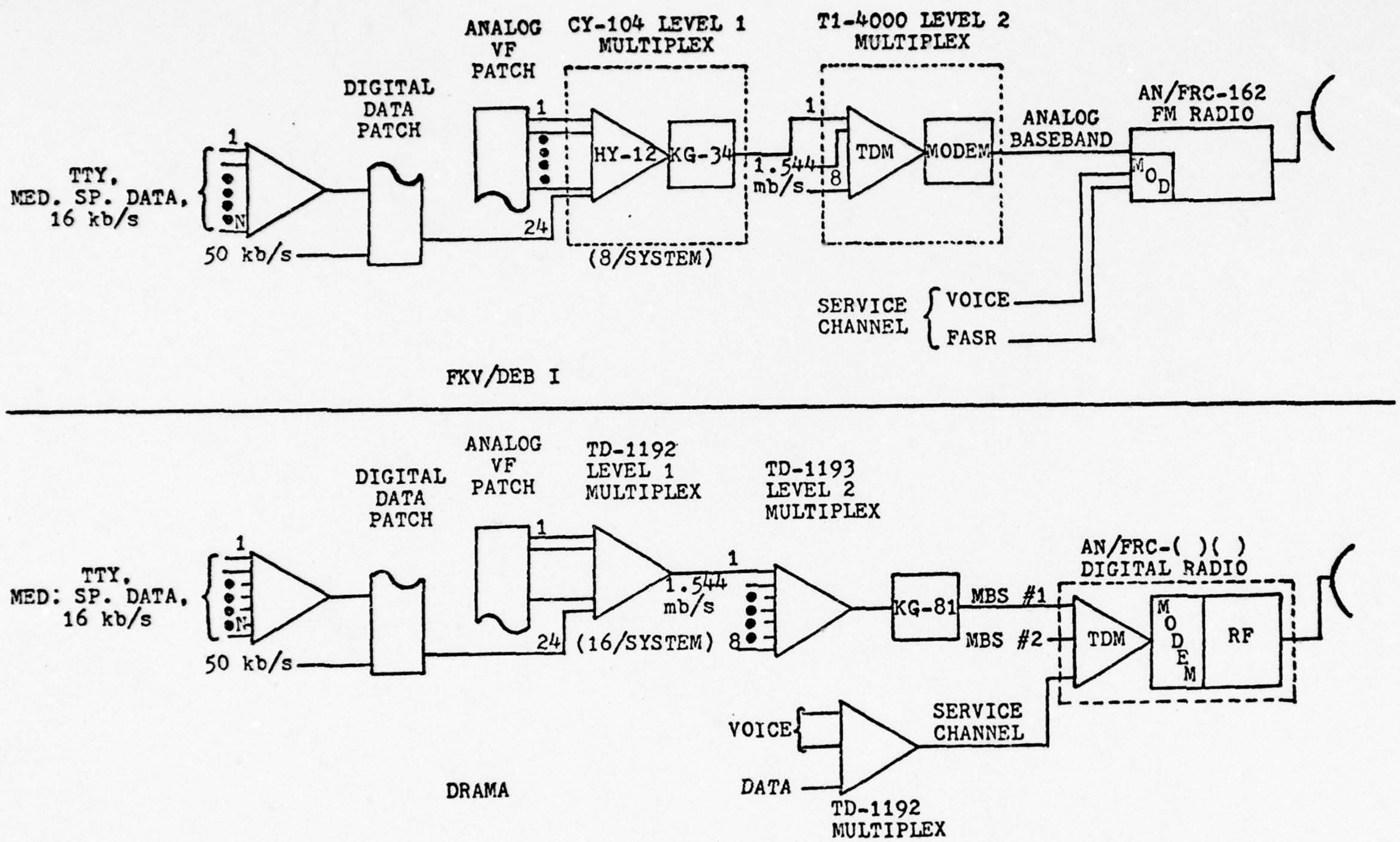


Figure 8-2. Comparison of FKV/DEB Stage I vs DRAMA Systems.

provide digital terrestrial connectivity for switched and non-switched networks and interconnect with the DSCS earth terminals, North Atlantic Treaty Organization (NATO), host nations, and digital tactical systems throughout western Europe. Bulk encryption of DEB traffic will minimize the interception of compromising information within the system. Figure 8-3 depicts the DEB project sites through Stage III.

An important aspect of this upgrade project is that DEB is the military forerunner of future systems which will require a minimum of operator and maintenance support utilizing unmanned and marginally manned facilities.

The DEB program is organized into four stages. DEB Stage I will provide 12 microwave radio links connecting sites in northern Italy with those in southern Germany, and will join with the Army FKV System at Vaihingen, Germany. Stage I will use the 3-level partial response for digital transmission. DEB Stage II and III will use DRAMA equipment and pure digital techniques. Both stages will connect central Germany with Belgium and the United Kingdom. DEB Stage IV will cover branch links for high priority or high volume subscribers throughout western Europe. Finally, the DEB DCS transmission system will strengthen system survivability by providing alternate transmission paths through the DSCS and digital tactical communications systems.

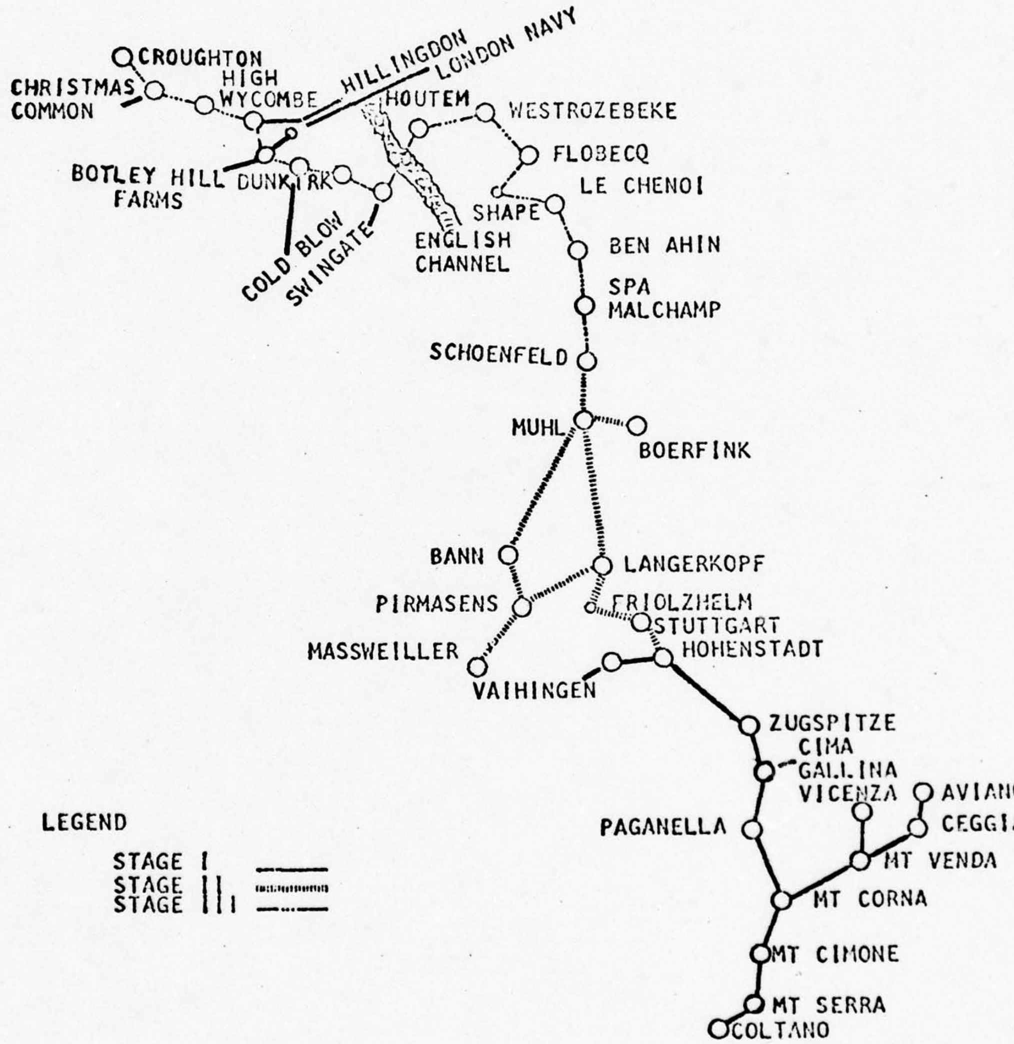


Figure 8-3. Digital European Backbone Phase I-III
(Source: Digital European Backbone(DEB) Program, Program Management and Implementation/Installation Plan, Figure 1.1, p. 2)

The Future—An All Digital Encrypted DCS

To this point in this project, we have discussed the invention and history of PCM, traced its growth in theory and in practical application, followed the evolution of equipments and the technologies they use, and analyzed the potential of these developments in commercial and military applications.

Since the formation of the Defense Communication System (DCS) in 1960, the Defense Communication Agency (DCA) and the MILDEPS have experienced an important learning process. The DCA, in the formulation of the Defense Communications System, successfully capitalized on certain on-going programs of the Military Departments while the programs were still in the growing stages. The Automated Voice Network (AUTOVON), the Automated Digital Network (AUTODIN), and the Automated Secure Voice Communications (AUTOSEVOCOM) all grew out of Army and Air Force programs. These combined programs form the "first generation" of the Defense Communications System based on analog transmission.

A Military requirement evolved for reasons of performance, economy, and security for an "all digital DCS". It was determined because of the immense worldwide inventory of existing analog plant and its remaining operational life that a transitional hybrid system containing PCM/TDM and FDM links was not only the most cost-effective solution, but a necessary predecessor to an all digital encrypted DCS which could be changed without sacrificing current or future capability and performance levels. Constraining

factors such as readily available hardware, available Military funding, and an affordable technology to accomplish the implementation, were encountered early. Further complications arose because of national and international considerations regarding excessive usage of the frequency spectrum by the application of a technology which was less spectral efficient than analog transmission.

Although compromises in broad, desirable, equipment capabilities were necessitated by restricted funding levels, high levels of performance and increased data capacity have been achieved through the use of innovative systems techniques.

The future brings the "second generation" of transmission systems based on the digital transmission technologies. AUDODIN II and AUTOSE-VOCOM II are evolutionary steps for the DCS. AUTODIN II will provide the capability of handling the increased digital computer traffic being generated throughout the DCS. Cryptographic techniques and equipment developed by the Joint Tactical Communications Program (TRI-TAC) will provide improved quality, expanded usage, and increased interoperability with tactical forces. The Defense Satellite Communications System upgrade in DSCS III will employ digital transmission and spread spectrum techniques, thereby providing improved anti-jamming capability for operation in a hostile electromagnetic environment.

The future of digital transmission in military communications offers great promise, but also presents many challenges. A forward-looking

Military must insure that all future transmission systems are integrated into and compatible with the existing plant to the maximum extent possible, and that the technology is economically adapted to the Military's true needs.

The Military's recognition of the need to develop adequate Operation and Maintenance (O&M) procedures prior to system implementation resulted in the establishment of training centers and intensive programs which produce competent O&M personnel, as evidenced in the technical maintenance of the FKV System. These training programs provide a necessary and effective compliment to the implementation of digital technology.

In conclusion, the first steps for a rational transition to a digital Defense Communications System have been made and have been proven to be responsive to the user's communications requirements. Trends and growth patterns of Military user requirements have been extensively evaluated and the results applied to the near term, and future transmission systems upgrades. Therefore a solid foundation has been laid for the continued transition to an "All Digital DCS." Through such programs, the DCA is strengthening the DCS's ability to provide security, survivability, flexibility, and economy for defense communications. All of these characteristics are essential for a strong, reliable, and practical DCS.

CHAPTER 8

Footnotes

1. R.E. Skerjanec and J.E. Farrow. <u>FKV Pilot Digital System Evaluation, OTM 77-238</u>, Institute of Telecommunications Sciences, Vol. I, July 1977, p. 2.

2. A. Vigants, "Space-Diversity Engineering." <u>The Bell System Technical Journal</u>, Vol. 54, No. 1 (January 1975), pp. 103-142.

3. R.E. Skerjanec, J.E. Farrow, and P.H. McQuate. <u>FKV Pilot Digital System Evaluation, OTM 77-238</u>, Institute of Telecommunication Sciences, Vol. III, July 1977, p. 17.

4. R.L. Wiggington and N.S. Nahman, "Transient Analysis of Coaxial Cables Considering Skin Effect," <u>Proceedings of the IRE</u>, No. 45, Feb. 1957, pp. 166-174.

5. Skerjanec, Farrow,and McQuate, <u>op. cit.</u>, p. 26-27.

6. Skerjanec and Farrow, <u>op. cit.</u>, p. 4.

7. Skerjanec, Farrow, and McQuate, <u>op. cit.</u>, p. 94.

8. Skerjanec and Farrow, <u>op. cit.</u>, p. 5.

9. R.G. DeWitt, "Digital Microwave Radio," <u>Telecommunications</u>, April 1975, p. 30.

10. Albrect P. Barsis. <u>A Proposed Five Year Plan in Radio Communication System Performance at Frequencies Between 10 and 30 GHz</u>. May 1974, p. ii.

11. International Radio Consultative Committee "CCIR Report 610 Digital Radio-Relay Systems: Compatibility between digital and FDM-FM radio-relay systems," <u>CCIR XIIth Plenary Assembly Geneva 1974</u>, Vol. IX, p. 138.

12. Tom M. Shimabukuro. "The DCS Circa 1980-82." Conference Record 1976 International Conference on Communications, Volume II, Philadelphia, June 14-16, p. 33-5.

13. Ibid., p. 33-6.

14. M. Ramadan, "Practical Considerations in the Design of Minimum-Bandwidth, 90-MB, 8-PSK Digital Microwave System." Technical Note. Collins Radio Group, Rockwell International Corporation, Dallas, Texas. (June 1977).

15. C.J.R. Pallemaerts, W.W. Rollins, and W.A.H. Wood. "Modulation Techniques for an 89 MB/S Digital Microwave Radio." Eastcom 1976, Washington, D.C., Sept. 28-29, p. 1.

16. Ibid., pp. 3-4.

17. R.W. Lucky, J. Salz, and E.J. Weldon, Jr., Principles of Data Communications, San Francisco, McGraw-Hill Book Company, 1968, pp. 50-51.

18. W.A.H. Wood, "Modulation and Filtering Techniques for 3 Bits/Hertz Operation in the 6 GHz Frequency Band." ICC Conference, Chicago, June 12-15, 1977, p. 1.

19. Jospeh Ferreira and Jack M. Nilles, "Five-Year Planning for Data Communications." DATAMATION, October, 1976, p. 56.

20. Electronic Systems Divisions, Air Force Systems Command. Program Management and Implementation/Installation Plan (PMI/IP) Digital European Backbone (DEB) Program. November 1, 1976, p. 1.

SELECTED BIBLIOGRAPHY

Books

Bennett, William R. and James R. Davey. Data Transmission. San Francisco, McGraw-Hill Book Company, 1965. 356 pp.

Boxall, Frank. Pulse Code Modulation in Telephony. Second Edition, Revised. Mountain View, VICOM, 1969. 68 pp.

Fagen, M.D. A History of Engineering and Science in the Bell System. Holmdel, Bell Telephone Laboratories, Incorporated, 1975. 1073 pp.

Hamsher, Donald H. Communication System Engineering Handbook. St. Louis, McGraw-Hill Book Company, 1967. 972 pp.

International Radio Consultative Committee. XIIIth Plenary Assembly, Geneva 1974, Volume IX, Fixed Service Using Radio-Relay Systems (Study Group 9). Coordination and Frequency Sharing Between Systems in the Fixed Satellite Service and Terrestrial Radio-Relay Systems (Subjects Common to Study Groups 4 and 9). International Telecommunication Union, Geneva, 1975. 409 pp.

International Radio Consultative Committee. XIIth Plenary Assembly, New Delhi, 1970, Volume IV, Part 1: Fixed Service Using Radio-Relay Systems (Study Group 9). Coordination and Frequency Sharing Between Communication-Satellite Systems and Terrestrial Radio-Relay Systems (Subjects Common to Study Groups 4 and 9). International Telecommunication Union, Geneva, 1970. 345 pp.

International Radio Consultative Committee. XIIth Plenary Assembly, New Delhi, 1970, Volume I, Spectrum Utilization and Monitoring. International Telecommunications Union, Geneva, 1970.

Lucky, R.W., J. Salz, and E.J. Weldon, Jr. Principles of Data Communications. San Francisco, McGraw-Hill Book Company, 1968. 433 pp.

Martin, James. Telecommunications and the Computer. Second Edition. Englewood Cliffs, Prentice-Hall, Inc., 1976. 670 pp.

Sams, Howard W. Reference Data for Radio Engineers. Second Edition. Kansas City, Howard N. Sams and Co., Inc. A subsidiary of International Telephone and Telegraph Corporation, 1975. 1266 pp.

Sunde, Erling D. Communication Systems Engineering Theory. New York, John Wiley and Sons, Inc., 1969. 512 pp.

Periodicals

"A 16-Year-Old Bottleneck that Could Jam up U.S. Defense." U.S. News and World Report. (March 8, 1976), pp. 89-91.

Andrews, Howard R. "Let's Take the Mystery Out of Modems." The Electronic Engineer. (July, 1972), pp. DC-5-DC-9.

Atal, B.S. and M.R. Schroeder. "Adaptive Predictive Coding of Speech." Bell System Technical Journal Vol. 49 (Oct. 1970), pp. 1973-1986.

Balcewicz, Joseph F., Martin Hecht, and H. Robert Mathwich. "The Effect of Tandem Band and Amplitude Limiting on the E_b/N_o Performance of Minimum (Frequency) Shift Keying (MSK). IEEE Transaction on Communications. (October, 1974). pp. 1525-1539.

Ball, Willis H. and Van C. Doubleday. "Expanding the Reins of Command." Signal. (January, 1977), pp. 38-42.

Becker, Roger J. "Computer Analysis Copes with Radio Network Interference." Microwaves. (August, 1972), pp. 9-10.

Beckerich, J. F. and J.H. Ingram, "Is 'Cross-Pol' the Way to Go for 11 GHz Digital LOS Radio." Telephone Engineer and Management. (November 15, 1976), pp. 1-5.

Bedrosian, Edward. "Spectrum Utilization by Efficient Channel Utilization." IEEE Communications Society Magazine. Vol. 15, No. 2 (March, 1977), pp. 20-27.

Blachowicz, L. F. "Digital Techniques Expand Defense Communications." Telecommunications. (November, 1972), pp. 30-34.

Boxall, Frank S. "Digital Transmission Via Microwave Radio, Part I." Telecommunications. (April, 1972), pp. 17-61.

Boxall, Frank S. "Digital Transmission Via Microwave Radio, Part II." Telecommunications. (May, 1972), pp. 41-54.

Boyes, Jon L. (Rear Admiral, USN). "Telecommunications for a Multiple-Mission Navy." Signal. (January, 1975), pp. 6-10.

Brennan, D.G. "Linear Diversity Combining Techniques." Proceedings of the IRE. (June, 1959), pp. 1075-1102.

Brogle, Albert P., Seymour Krevsky, and Leo H. Wagner. "The Global Digitally Switched Communications Systems Evolution." Symposium on Computer-Communications Networks and Teletraffic, Polytechnic Institute of Brooklyn. (April 4-6, 1972), pp. 547-556.

Brugger, Richard D. "Information: Its Measure and Communication." Computer Design. (November, 1970), pp. 115-120.

Burnside, Don. "The Pioneering MCI System." Microwave Systems News. (August, 1970), pp. 12-13.

Bylinsky, Gene. "Datran's Hazardous High-Wire Act." Fortune. (February, 1976), pp. 131-139.

Cariolard, G.L. and Franco Todero. "A General Spectral Analysis of Time Jitter Produced in a Regenerative Repeater." IEEE Transactions on Communications. Vol. COM-25, No. 4 (April, 1977), pp. 417-426.

Chaney, W.G. "Equalization of Telephone Lines for Data Transmission." Electronic Communicator. (May/June, 1968), pp. 4-8.

Cole, J.E. "Design Techniques for Wideband." Electronic Industries. (November, 1965), pp. 58-63.

Collier, M.E. and K.C. Kao. "Fibre-Optic Systems in Future Telecommunication Networks." Telecommunications. (April, 1977), pp. 25-32.

Collins, Arthur A. "Are We Committed to Change in Telecommunication Systems." A Presentation to the 1974 AFCEA Conference Panel. "A Time for Innovation." June 1, 1974, pp. 1-8.

"Communications and Microwave Technology." IEEE Spectrum. (January, 1977), pp. 43-48.

Cox, John E. "Western Union Digital Services." Proceedings of the IEEE. Vol. 60, No. 11 (November, 1973), pp. 1350-1368.

Crochiere, R.E., J.L. Flanagan and S.A. Weber. "Digital Coding of Speech in Sub-bands." The Bell System Technical Journal. Vol. 55, No. 8 (October, 1976), pp. 1069-1085.

Cuccia, C. Louis. "New PCM Techniques Stress Spectrum and $ Conservation, Part I." Microwave System News. (January, 1977), pp. 57-64.

Cuccia, C. Louis. "New PCM Techniques Stress Spectrum and $ Conservation, Part II." Microwave Systems News. (February, 1977), pp. 37-54.

Cuccia, C. Louis, and Richard S. Davies. "Operation of Information Satellites in an Interference Environment." The Microwave Journal. (June, 1972), pp. 33-42.

Cuccia, C. Louis, and James J. Spilker, Jr. "Wideband Spectrum Utilization Above 10 GHz for Communications and Monitoring the Ecology." The Microwave Journal, (November, 1971), pp. 24-30.

"Data Transmission: Principles and Problems." GTE Lenkurt Demodulator. (August, 1974), pp. 1-7.

"DATRAN: Why?" Microwave Systems News. Vol. 6, No. 5 (November, 1976), p. 28.

Deloraine, E. Maurice, and Alec H. Reeves. "The 25th Anniversary of Pulse Code Modulation." IEEE Spectrum. (May, 1965). pp. 56-63.

DeWitt, R.G. "Digital Microwave Radio." Telecommunications. (April, 1975), pp. 25-31.

"Digital Data System." GTE Lenkurt Demodulator. (January/February, 1977), pp. 2-8.

"Digital Microwave Transmission Engineering Symposium." Rockwell International, Collins Commercial Telecommunication Division. Dallas, Texas. (April 18-21, 1977).

Dougherty, Harold T. And Ernest K. Smith. "The CCIR and Radio Propagation-A Mini Review." IEEE Transactions on Antennas and Propagation. (November, 1976), pp. 910-912.

Eger, John M. "An Epitaph for DATRAN." Datamation. (December, 1976), pp. 199.

"Extended Length PCM Systems." GTE Lenkurt Demodulator. (February, 1974).

Falk, Howard. "Picturephone and Beyond." IEEE Spectrum. (November, 1973), pp. 45-49.

Ferreira, Joseph and Jack M. Nilles. "Five-Year Planning for Data Communications." Datamation. (October, 1976), pp. 51-57.

Fleig, William E. "A Stuffing TDM for Independent T1 Bit Streams." Telecommunications. (July, 1972), pp. 23-32.

Fox, Kerry R. and John F. Beckerich. "The Maturing of Digital Microwave Radio." Signal. (April, 1976), pp. 1-6.

Franklin, R.H. and H.B. Law. "Trends in Digital Communication." IEEE Spectrum. (November, 1966), pp. 52-58.

Gallagher, Edward F. "The Military Goes Digital." IEEE Spectrum. (February, 1977), pp. 42-45.

Gallawa, R.L. "Optical Waveguide Technology." Conference Proceedings World Telecommunications Forum, Geneva, Switzerland, October 8-9, 1975, p. 1.3.2.1 - 1.3.2.6.

Gelnovatch, V.G. "Microwave Circuit and Device Development." Telecommunications. Vol. 19, No. 12 (December, 1976), p. 29.

Gill, Walter. "Digital Microwave Radio Shortens the Miles." The Electronic Engineer. (June, 1972), pp. DC-5 - DC-11.

Gray, James S. "Quadraphase PSK Modulation Technique Permits Data Transmission at 1 Gbps." Communications Design. (December, 1972), pp. 3-8.

Hardeman, Lyman J. "Tech Sessions Highlight mm-Wave Trends and Low-Noise Amplifier Techniques." Microwaves. (August, 1970), pp. 64-67.

Havens, Edward A. "Two Hundred Years of Communications." Signal. (November, 1976), pp. 33-35.

"Heterodyne Repeaters for Microwave." The Lenkurt Demodulator. Vol. 13, No. 8, August, 1964, 7 pp.

Houser, Thomas J. "OTP Today: Policymaking for the "Age of Information." Signal. (January, 1977), pp. 16-18.

Huang, Thomas S. "PCM Picture Transmission." IEEE Spectrum. (December, 1965), pp. 57-63.

"Increasing PCM Span-Line Capacity." GTE Lenkurt Demodulator. (May/June 1976), pp. 1-9.

Jacobs, Ira. "Lightwave Systems Moving Toward Telecommunications Use." Signal. (May/June, 1977), pp. 41-46.

Jacobs, Ira and Stewart E. Miller. "Optical Transmission of Voice and Data." IEEE Spectrum. (February, 1977), pp. 33-41.

Jayant, Nuggehally, S. "Digital Coding of Speech Waveforms: PCM, DPCM, and DM Quantizers." Proceedings of the IEEE. (May, 1974), p. 611-632.

Jenkins, James. Lt. Col. USA. "The Government Communications Planning Program." Signal. (August, 1976), pp. 98-100.

Johnson, Charles P. "Data Communications - The Evolution of '76." Telecommunications. (January, 1976), pp. 41-44.

Johnson, L. Bruce. "Improve Microwave Performance with Digital Modulation." Telephony (reprint). (May 8, 1972).

Knapp, N. and N.E. Snow. "Digital Data System: System Overview." Bell System Technical Journal. Vol. 54, No. 5 (May-June, 1975), pp. 811-832.

Levine, R.H. "The Evolving DCS: Introduction and Overview." Conference Record, 1976 International Conference on Communications. Vol. II, June 14-16, 1976, Philadelphia. pp. 33-2 — 33-4.

"Liquidation of Wyly's DATRAN, The" Datamation, (October, 1976), pp. 144-145.

Massard, M.J. "Performance Analysis of Microwave Communications Systems by Digital Computer." The Microwave Journal. (August, 1970), pp. 35-41.

McCalmont, Arnold M. "Communications Security for Voice-Techniques, Systems, and Operations." Telecommunications. (April, 1973), pp. 35-42.

Mennie, Don. "Communications and Microwave." IEEE Spectrum. (January, 1975), pp. 43-48.

"Military Communications Market." Telecommunications. (December, 1976), p. 16.

"Military Communication Markets." Microwave Journal. International Edition. Vol. 20, No. 2 (February, 1977), p. 40.

"Military Versus Commercial Carrier System Design." The Lenkurt Demodulator. Vol. 10, No. 4 (April, 1961), p. 131.

"$30 Million Program for MCI During Year." Communications News. (July, 1977), p. 3.

Muth, R.J., J.W. Shipman and J.E. Toffler. "Factors Affecting Choice of Modulation Techniques for Data Transmission." Telecommunications. (March, 1969), pp. 17-22.

Oliver, B.M., J.R. Pierce, and C.E. Shannon. "Philosphy of PCM." Proceedings of the IRE. Vol. 36 (November, 1948), pp. 1324-1331.

Pallemaerts, C.J.R., W.W. Rollins, and W.A.H Wood. "Modulation Techniques for an 89 MB/S Digital Microwave Radio." EASTCOM 1976, Washington, D.C., (September 28-29), pp. 1-6.

"PCM-FDM Compatibility Part 1." GTE Lenkurt Demodulator. (July, 1971), pp. 1-7.

Pierce, John R. "Some Practical Aspects of Digital Transmission." IEEE Spectrum. (November, 1968), pp. 63-70.

Plotkin, I.P. "The Performance Monitor Problem for a Digital DCS." National Telecommunications Conference. November 26-28, 1973, Atlanta, Volume I, p. 4B-1.

Plummer, William E. "Problems of Frequency Management." Signal. (September, 1968), p. 34-7.

Polishuk, Paul, Dr. "Telecommunications and the Energy Crisis." Office of Telecommunications, U.S. Department of Commerce, 1973.

Puckorius, Theodore D. "Winds of Change in Communications and Computers." Signal. (September, 1976), pp. 18-22.

Reeves, Alec H. "The Past, Present and Future of Pulse Code Modulation." Telephony. (July 6, 1968), pp. 13-17.

Renner, John J. "Twenty Years of Microwave Point to Point." The Microwave Journal. (June, 1968), pp. 32-6.

Riceman, John P. "National Defense Policy and Command and Control Communications." Signal. (January, 1975), pp. 31-34.

Robbins, Jack B. (M/Gen. USAF) "The Convergence of Computer and Communication Technologies." Signal. (January, 1975), pp. 21-23.

"Satellite-Computers-Communications." Telecommunications. (October, 1976), p. 15.

Saunders, Morton J. "Cross Polarization at 18 and 30 GHz due to Rain." IEEE Transactions on Antennas and Propagation. (March 1971), pp. 273-277.

Schindler, H.R. "Delta Modulation." IEEE Spectrum. (October, 1970), pp. 69-78.

Schneider, Philip. "Satellite Technology Increases Transmission Reliability and Lowers Cost." Telecommunications. (May, 1977), pp. 22-24.

Scott, W.G., H.S. Luh and E.W. Matthews. "Design Tradeoffs for Multibeam Antennas in Communication Satellites." IEEE Communications Society Magazine. (March, 1977), pp. 9-18.

Seitz, Niel B. and Peter M. McManamon. "Performance Measures for Digital Communication Services." Business Communications Review. (March-April 1976), pp. 26-34.

Shimabukuro, Tom M. "The DCS Circa 1980-82." 1976 International Conference on Communications, Volume II. Philadelphia, June 14-16. pp. 33-5 — 33-10.

Shultz, Donald O. "DCS Transmission Network: 1980-82." Conference Record, 1976 International Conference on Communications, Volume II June 14-16, 1976, Philadelphia. pp. 33-11 to 33-16.

Smith, Ernest K. "The History of the ITU, with Particular Attention to the CCITT and the CCIR, and the Latter's Relations with URSI." Radio Science. (June, 1976), Volume II , Number 6, p. 497-507.

Smith, William H. and A.C. Walker, "PCM Microwave Links." Telecommunications. (April, 1973), pp. 25-30.

"SP Communication's Gus Grant and Rex Hollis Talk About DATRAN." Communications News. (July, 1977), p. 26.

"Supercomponent Update - Current and Future Trends." Microwave Journal. (May, 1977), pp. 16-20.

Thomas, David T. "Cross-polarization distortion in microwave radio transmission due to rain." Radio Science. Volume 6, No. 10 (October, 1971), pp. 833-839.

Utlaut, William F. "Review of Important Problems in Wave Propagation Affecting Future Telecommunication System Performance." Proceedings of World Telecommunications Forum Technical Symposium, Geneva, Switzerland. October 6-8, 1975, p. 3.1.8.1—3.1.8.8.

Vigants, A. "Space-Diversity Engineering." The Bell System Technical Journal. Vol. 54, No. 1 (January, 1975), pp. 103-142.

Watson, P.A. "Attenuation and Cross-Polarization Measurements at 11 GHz." Proceedings of the IEEE International Conference on Communications. June 1972-Philadelphia. pp. 2-21 to 2-24.

Watson, P.A., S.G. Hobrail and F. Goodall. "Mutual Interference Between Linear Crosspolarized Radio Channels at 11 GHz." Electronic Letters. Vol. 7, No. 3 (July 1, 1971), pp. 374-377.

Wiggington, R.L. and N.S. Nahman. "Transient Analysis of Coaxial Cables Considering Skin Effect." Proceedings of the IRE. No. 45 (February, 1957), pp. 166-174.

Williams, Val J. "Digital Modulation Techniques: Reply Comments of NABER," Action. Vol. VIII, No. 1 (January, 1972), p. 10.

Wood, W.A.H. "Modulation and Filtering Techniques for 3 Bits/Hertz Operation in the 6 GHz Frequency Band." ICC Conference, Chicago, June 12-15, 1977. pp. 1-5.

Worley, Allen R. "The DATRAN System." Proceedings of the IEEE. Vol. 60, No. 11 (November, 1972), pp. 1357-1368).

Zenko, W. "Digital Microwave Communications for the Power Utilities." Presented at the American Public Power Association, Engineering and Operations Workshop, February 25, 1975, Seattle, Washington.

Government Documents

Air Force Communications Service, Headquarters. Operational Test and Evaluation of PCM/TDM Equipment. 1 January 1972.

Air Force Communications Service, Headquarters. DCS Operational Test and Evaluation of PCM/TDM Equipment, Phase I Testing Test Report. September 6, 1973.

Air Force Communications Service, Headquarters. DCS Operational Test and Evaluation of Pulse Code Modulation/Time Division Multiplex (PCM/TDM) Equipment, Test Report August 1973 - February 1974.

American Telephone and Telegraph Company, Reply Comments to Docket No. 19311, January 17, 1972.

Avantek, Response to Notice of Inquiry Docket No. 19311 Digital Modulation Techniques in Microwave Radio. November 15, 1971.

Barsis, Albrecht P., A Proposed Five-Year Plan in Radio Communication System Performance at Frequencies Between 10 and 30 GHz. Fy 1975-1979. U.S. Department of Commerce, May, 1974.

Bower, Cpt. Harold F. and 1Lt. Edward F. New. Digital Transmission Evaluation Project RDS-80: Final Report, CCC-CED-75-DTEP-005. Headquarters, U.S. Army Communications Electronics Engineering Installation Agency, Fort Huachuca, Arizona, March, 1975.

Bower, Capt. H.F., 1Lt. E.F. New, D.M. Laida, A. Hemmila. Digital Transmission Evaluation Project, RDS-80G Test, Final Report, CCC-CED-DTEP-004. Headquarters U.S. Army Communications-Electronics Engineering Installation Agency, Fort Huachuca, Arizona, February 1975.

Bower, Cpt. H.F., Cpt. J.E. Hamant, and 1Lt. E.F. New. Digital Transmission Evaluation Project Equipment Comparison: BER vs RSL, C/I, Power Spectra, Special Report, CCC-SR-75-DTEP-007. Headquarters U.S. Army Communications-Electronics Engineering, Installation Agency, Fort Huachuca, Arizona, August 1975.

Bower, Cpt. H.F., Cpt. J.E. Hamant, and 1Lt. E.F. New. Digital Transmission Evaluation Project MW-518 (QPSK) Test, Final Report CCC-CED-75-DTEP-008, Headquarters U.S. Army Communications-Electronics Engineering Installation Agency, Fort Huachuca, Arizona. October, 1975.

Crombie, Douglass D., Lowering Barriers to Telecommunications Growth. OT Special Publication 76-9. U.S. Department of Commerce, November, 1976, pp. 119.

Data Transmission Company. Reply Comments of the Data Transmission Company (DATRAN). January 17, 1972.

Defense Communications Engineering Center. Digital Transmission System Design Technical Report No. 3-74, March, 1974.

Defense Communications Engineering Office, Preliminary Report: PCM/TDM System Design Verification Test Program, 25 February, 1972.

Defense Communications Engineering Office, Applications of Pulse Code Modulation (PCM) Time Division Multiplex (TDM) and Digital Transmission in the DCS. 7 January 1972.

U.S. Army Communications-Electronics Engineering Installation Agency, Fort Huachuca, Arizona. Digital Transmission Evaluation Project (DTEP) Letter Report: Engineering Analysis of VICOM 4000 Series Digital Multiplexer Baseline Test Results, CCC-CED-DTEP-LRL. December, 1974.

Department of Defense, Electromagnetic Compatibility Analysis Center (ECAC). Technical Report No. ESD-TR-73-012 EMC Analysis of the DCS Frankfut-Koenigstuhl-Vaihingen Upgrade. May, 1973.

Electromagnetic Compatibility Analysis Center. Annual Report 1976.

Electronic Systems Division, Air Force Systems Command. Program Management and Implementation/Installation Plan (PMI/IP) Digital European Backbone (DEB) Program. November 1, 1976.

Electronic Systems Division, Air Force Systems Command. Program Management and Implementation/Installation Plan (PMI/IP) Digital European Backbone (DEB) Program. May 16, 1977.

Farrow, J.E. An Analysis of Industry Responses to FCC Docket 19311 Relating to the Use of Digital Modulation on Microwave Radio Links OT TM-120. U.S. Department of Commerce, Office of Telecommunications/Institute for Telecommunications Sciences (December, 1972).

Farrow, J.E. and R.E. Skeyanec. AN/FRC-80(v)3: Retune and Time Division Multiplex Interference Investigation OT TM 74-182. Department of Commerce/Office of Telecommunications (October, 1974).

Federal Communications Commission, The. Docket No. 19311, Notice of Inquiry. Adopted: September 8, 1971; Released: September 15, 1971.

Federal Communications Commission, The. Docket No. 19311, Order. Adopted: December 9, 1971; Released: December 13, 1971.

Federal Communications Commission, The. Notice of Proposed Rule Making. Adopted: May 3, 1973; Released: May 8, 1973.

General Telephone and Electric Company. Comments of GTE Lenkurt Incorporated to Docket No. 19311. November 15, 1971.

Grace, V., O. Halpeny, F. Ricci, and D. Schutzer. DCS System Control Concept Formulation Technical Report No. 5-74. Defense Communications Engineering Center, Reston, Virginia. February, 1974, pp. 51.

Hamant, Cpt. James E., O.P. Connell and Henry S. Walczyk. Digital Transmission Evaluation Project DR8A Test Final Report, CCC-CED-77-DTEP-012 . Headquarters , U.S. Army Communications Electronics Engineering Installation Agency, Fort Huachuca, Arizona. (April, 1977).

Hamant, Cpt. J.E., Cpt. J.J. McDonnell, and Cpt. E.F. New. Digital Transmission Evaluation Project Final Evaluation Report, Phase I. Headquareters U.S. Army Communications-Electronics Engineering Installation Agency, Fort Huachuca, Arizona. September, 1976.

Jessen, F.A. Microwave Data Transmission Test Program Digital Applique Unit RADC-TR-76-268. Rome Air Development Center, Air Force Systems Command, Griffis Air Force Base, New York, 13441.

Juroshek, John R. Performance of Digital Modems with Co-channel Interference and Gaussian Noise. OT Report 76-82. U.S. Department of Commerce, Office of Telecommunications, February, 1976.

Kirk, K.W. and J.L. Osterholz. DCS Digital Transmission System Performance, Technical Report No. 12-76. Defense Communications Engineering Center, Transmission System Development Branch, R220, Reston, Virginia, November, 1976.

McDonnell, Cpt. J.J., Cpt. E.F. New, SFC S.T. Schoch. DEB Stage I - Conus Link Testing, Interim Report. Headquarters U.S. Army Communications Electronic Engineering Installation Agency Fort Huachuca, Arizona. October, 1976.

Microwave Communications Incorporated. Comments of the MCI Carriers to Docket No. 19311, November 15, 1971.

National Security Agency, Communications Security Organization. Continuous Variable Slope Delta Modulation. May, 1973.

New, 1Lt Edward F. Digital Transmission Evaluation Project 23P2B Sensor Logic Switch Test, Final Report CCC-SR-75-DTEP-009. Headquarters U.S. Army Communications-Electronics Engineering Installation Agency, Fort Huachuca, Arizona. September, 1975.

New, Cpt. Edward F. Digital Transmission Evaluation Project AN/FRC-162 Test Final Report CCC-CED-76-DTEP-011. Headquarters U.S. Army Communications-Electronics Engineering Installation Agency, Fort Huachuca, Arizona. May, 1976, pp. 61.

Office of Telecommunications Policy. Activities and Programs, 1975-1976. Executive Office of the President.

Office of Telecommunications Policy. The Radio Frequency Spectrum: United States Use and Management. Executive Office of the President (January, 1973).

Office of Telecommunications Policy. Manual of Regulations and Procedures for Radio Frequency Management. Executive Office of the President (Revised May, 1977).

Office of Telecommunications Policy/Interdepartment Radio Advisory Committee. Report for the Period January 1-June 30, 1976.

Radtke, Jerald J., Colonel. Program Management and Implementation/ Installation Plan. Digital European Backbone (DEB) Program. Electronic Systems Division Air Force Systems Command, Hanscom Air Force Base, Mass. 1 November 1976.

Skerjanec, Richard E. An Evaluation of the Baseband Diversity Switch Applied to Digital-FM Operation. Letter Report (March 1973) to the U.S. Army Communications Command Fort Huachuca, Arizona.

Skerjanec, R.E. and J.E. Farrow. FKV Pilot Digital System Evaluation, Final Report, System Summary. Vol. I, Institute of Telecommunication Sciences, July, 1977.

Skerjanec, R.E. and J.E. Farrow. FKV Pilot Digital System Evaluation, Final Report, Operation and Maintenance Analysis, Vol. II, Institute of Telecommunications Sciences, July, 1977.

Skerjanec, R.E., J.E. Farrow, and P.L. McQuate. FKV Pilot Digital System Evaluation, Final Report, Engineering Analysis, Vol. III, Institute of Telecommunications Sciences, July, 1977.

Skerjanec, R. Test Results for Digital Testing of the Candidate Radios for the DCS Microwave Radio. OT Technical Memorandum 73-137C. U.S. Department of Commerce, April, 1973.

Smith, D. and F.G. Kimmett. Measurement of Interference Effects Between TDM-FM and FDM-FM Microwave Systems.OT TM 75-194. U.S. Department of Commerce, Office of Telecommunications (March, 1975).

Smith, David R. "Performance Assessment of Digital Transmission Systems." National Telecommunications Conference, Vol. I, November 26-28, 1973, Atlanta Georgia.

Thompson, M.C., H.B. Janes. An Analysis of Deep Fading in the 10 to 40 GHz Band On a Line-of-Sight Path, OT Report 75-69. U.S. Department of Commerce/Office of Telecommunications. July, 1975.

United States Army Communications Command. CE Project Communications Electronics Mission Order for the Digital Transmission Evaluation Project. October, 1973.

United States Army Strategic Communications Command. Program Concept Plan for the Digital Transmission Evaluation Program (DTEP). August, 1973.

United States Army Strategic Communications Command. Concept Plan for PCM/TDM Digital Transmission Application Project (DTAP) Engineering and Operational Testing. May, 1972.

United States General Accounting Office. Information On Management and Use of the Radio Frequency Spectrum-A Little Understood Resource. September 13, 1974.

Letters

Defense Communications Agency Letter 470 to Commander U.S. Army Strategic Communications Command, Ft. Huachuca, Arizona. Subject: DCS Digital Microwave Radio, PCM and Digital Multiplex, Dated 25 June 1973.

Federal Ministry for Posts and Telecommunications Letter to United States European Command, Subject: Microwave Radio-RF Bandwidth, Dated October 2, 1973.

Industrial Literature

"MDR-11/DMX-13 Microwave Digital Radio System." Collins Radio Group, Rockwell International. (1977).

"Transmission of Pulse Code Modulation on DCS Microwave Radio, Optimization Test, Test Report." Collins Radio Company. (September 10, 1973).

"Microwave PCM System." Nippon Electric Company, Limited. Japan.

"PSB-6004 Digital Multiplexer Description, Operation and Theory of Operation." VICOM (April, 1972).

Ramadan, M. "Practical Considerations in the Design of Minimum - Bandwidth, 90-MB, 8-PSK Digital Microwave System." Collins Radio Group, Rockwell International Corporation.

"Technical Report on Field Performance of the Raytheon RDS-80 Digital Microwave System." Raytheon Data Systems. (April 5, 1973).

Walker, A. "PCM Multiplexers for Microwave." VICOM.

Walker A., and R. Rearwin. "Digital Modulation Techniques." VICOM/ Microwave Associates.

Williams, J.L. "Reliability Considerations for Microwave Systems." Collins Radio Company.

Williams, J.L. "The Worth of High-Reliability Equipment in a Communication System." Collins Radio Company.

APPENDICES

APPENDIX A

RDS-80 SYSTEM THEORY OF OPERATION

1. Terminal Station

The basic elements of a 1200 channel RDS-80 system terminal are shown in Figure A-1. There are three radio units and three multiplexer units with associated switching equipment for hot standby equipment protection. Each radio or multiplexer unit handles up to 600 channels or 25 T1 lines. Two radios are used to achieve 1200 channel operation on a single radio frequency in the 10.7 to 11.7 GHz frequency band by being connected to opposite polarizations of the same antenna.

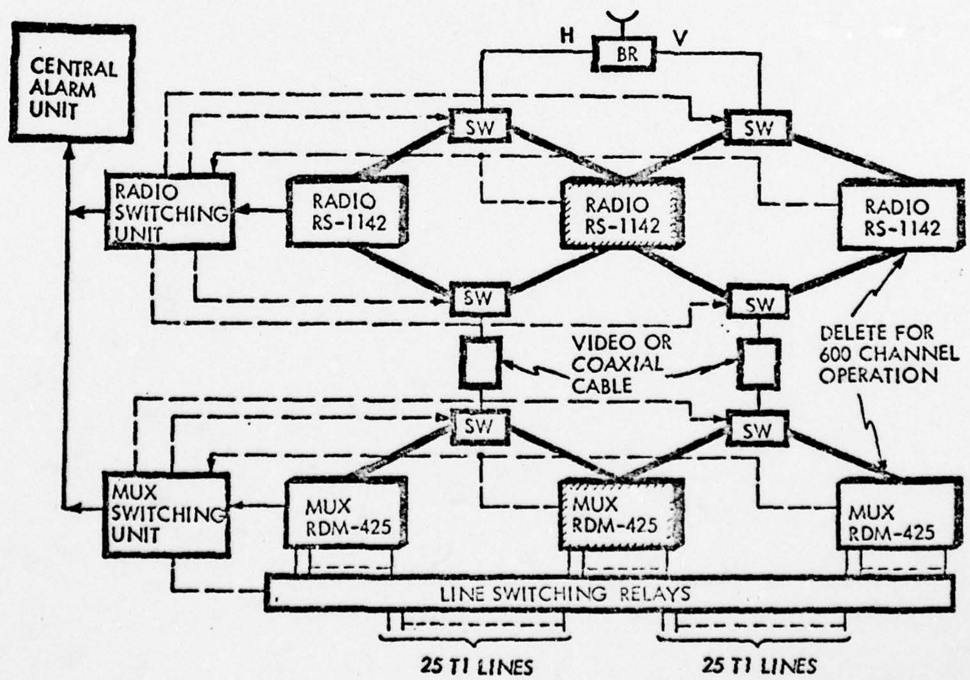


Figure A-1. RDS-80 1200 Channel Terminals, Block Diagram

Although both radios operate at the same frequency, system performance is degraded only a negligible amount because the digital detection circuits can withstand interference caused by cross-polarized operation as low as 14 db. With the dual polarization scheme, the number of digital voice channels per radio frequency allocation becomes approximately equal to that attainable in typical FDM/FM systems.

A third radio (shaded in Figure A-1), connected in hot standby, is automatically switched to the horizontal or vertical polarization channel on failure of either of the two on-line radios. Twelve sensing circuits in each radio detect faults and cause automatic switchover of the standby unit. Solid state diode switching is employed in the waveguide switch.

Automatic hot standby switching of the multiplexer equipment is also provided, based on failure of the 40 Mb/s (supergroup) portion only. When switchover occurs, the entire standby multiplexer, wire line driver and wire line receiver units are placed on-line and the input T1 lines are switched from the failed unit to the standby unit.

Manual switchover, for fault isolation or equipment off-line test, is also provided. Switching occurs independently in the radio and multiplexer equipment. Transmit and receive sections of the radio and multiplexer units are also switched independently.

Signals enter and leave the system from PCM channel banks or T1 span terminating equipment at a transmission rate of 1.544 Mb/s. The multiplexer units (RDM-425) provide a compatible interface to these signals in bit rate, signal type (bipolar), and level. Any signal compatible with Western Electric D1, D2, or D3 transmission signals will be accepted by the RDS-80 at its transmit side, and the RDS-80 will return a compatible signal to interface equipment on the receive side.

Up to 25 T1 lines can be combined in an RDM-425 multiplexer unit to produce a 40 Mb/s (600 channel) output. Loading can vary from 0 to 25 lines with no effect on system performance. Pulse stuffing is employed in the multiplex operation, which allows all inputs to be separately clocked and thereby eliminates any synchronization requirements on T1 lines or PCM banks. The pulse stuffing operation can easily handle timing jitter produced by any reasonable number of T1 line repeaters in tandem.

AD-A051 789 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO F/G 17/2.1
MILITARY DIGITAL MICROWAVE TRANSMISSION: PAST, PRESENT, FUTURE.(U)
AUG 77 R E BRACKETT, W E CARTER, J J SOLTIS
UNCLASSIFIED AFIT-CI-78-45 NL

4 OF 4
AD
A051789

END
DATE
FILMED
5-78
DDC

2. Repeater Station

Figure A-2 is a block diagram of a repeater station, which consists of back to back radio bays. At the radio receiver, signals are demodulated and regenerated to digital form. Hence, the system is regenerative and the digital signal (with separate timing line) is connected directly to the outgoing transmitter. Normally, in repeater stations, a wire line entrance link is not required since both radio bays are likely to be located close together.

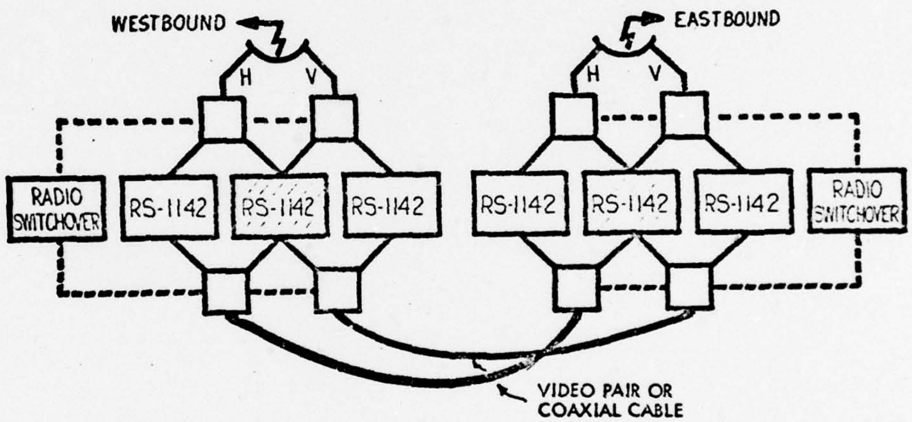


Figure A-2. Repeater Station, Block Diagram

Figure A-3 shows a drop repeater in which 600 channels or one supergroup is dropped at a repeater while the other is carried through on a 600 channel leg. The dropped supergroup eventually connects to a 600 channel multiplexer bay at the repeater location or at a remote location via an entrance link cable system. Another 600 channel supergroup can be inserted at this repeater station to take the place of the dropped supergroup.

BEST AVAILABLE COPY

No requirements of synchronizing the separate supergroups are imposed on the system by supergroup drop and insert applications. All supergroup (40 Mb/s) signals are generated from separate clocks in the transmit section of the originating multiplexer unit. This clock is carried through the system in the supergroup bit stream to the receive side of the terminating multiplexer unit.

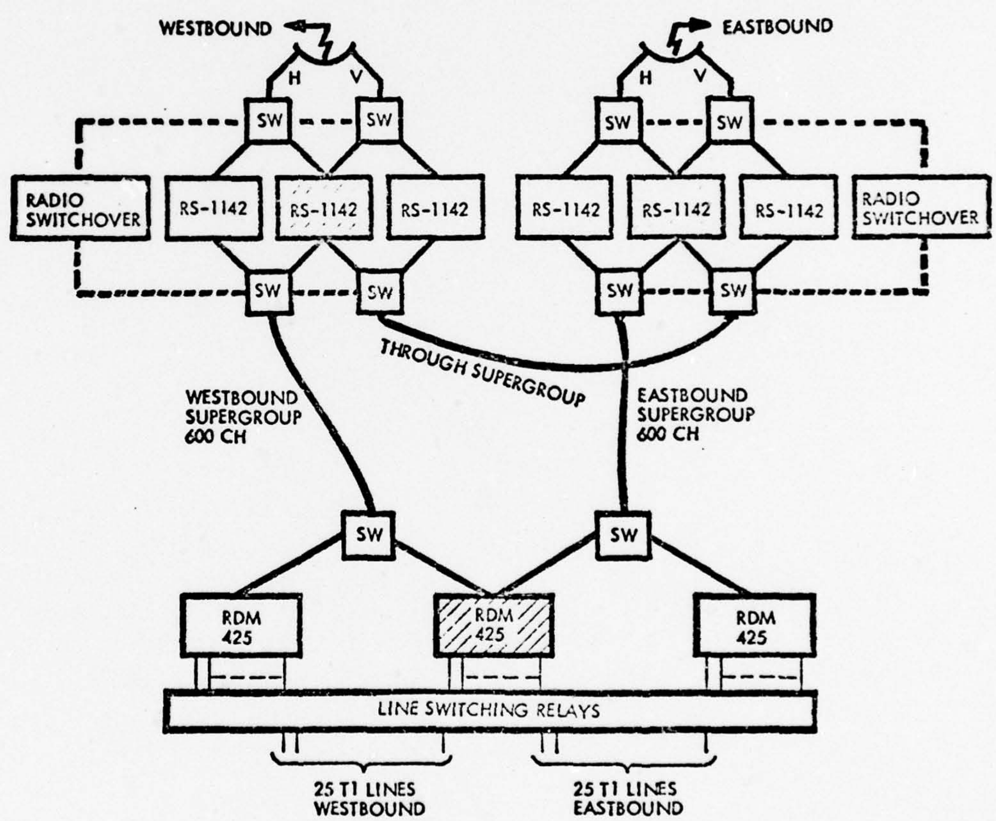


Figure A-3. Drop and Insert Repeater, Block Diagram

3. Functional Description

Figure A-4 shows the signal flow through the system and the primary functional circuit elements. A T1 line signal enters the transmit side of the multiplexer group unit, which converts the bipolar signal to binary NRZ and performs thepulse stuffing operation separately on each incoming group.

The group signals are combined on a bit by bit basis in the transmit common circuits, which arrange the bits in a frame format, inserting framing pulses and pulse deletion control information for the far end receiver. Timing pulses for the transmit group units and common circuits are developed from a transmit master oscillator, which establishes the multiplexer output bit rate of 40. 15 Mb/s.

Binary NRZ data out of the multiplexer is converted to diphase, a much more convenient signal for cable transmission because of the ease of combining and recovering timing with/from the data signal. The diphase signal is passed through a baseband amplifier to the balanced pair of 16 PEVL cable connecting the multiplexer and radio bays. Length of cable between bays is limited to 2000 feet.

At the receive end of the cable, the signal is amplified and equalized for different lengths of cable. Equalization is coarse, requiring only the choice of permanent settings for lengths of 0-500, 500-1000, 1000-1500, or 1500-2000 feet. Bit timing is recovered from the diphase signal in a phase locked loop and is used to sample the received signal at the appropriate point to make the 1 or 0 detection decision. The detector output is reconstructed diphase data, which is then converted back to binary NRZ.

Data and timing signals are sent to the digital encoder, which performs two operations on the bit stream. First, a serial to parallel encoding operation is performed, which converts the single bit stream into two separate streams that feed each half of the four phase modulator. This effectively transforms pairs of bits into four symbols (00, 11, 10, 01) and reduces the symbol rate from 40 to 20 million per second. The encoder also differentially encodes each separate bit stream by transmitting to the modulator the change in bit state rather than the bit itself. This protects against 1-0 inversion of the information in the transmission system, which could be caused in several ways.

The two bit streams are fed to the quadrature phase shift keyed (QPSK) modulator, which transforms the symbols above into one of four possible phases of a 70 MHz carrier signal, the phases being 90 degrees apart. Phase of the carrier signal is changed at a maximum rate of 20 million per second, the symbol rate.

Next the signal is upconverted from 70 MHz to a center frequency within the 10.7 to 11.7 GHz band by mixing it with a programable reference frequency from the AFC loop. The resulting RF signal is amplified to 30 dbm in the power amplifier (ADA). Control circuits are provided so that the power amplifier is muted if the AFC error voltage is too high, the AFC is out of lock, or modulation fails.

A waveguide filter is placed at the power amplifier output to eliminate out of band signals and to shape the transmitted spectrum to meet frequency coordination requirements and FCC rules.

Received RF signals enter the receiver, first passing through the receive waveguide filter, which rejects spurious signals outside of the operating bandwidth. This is a broad filter and is not the main receiver bandwidth shaping element.

BEST AVAILABLE COPY

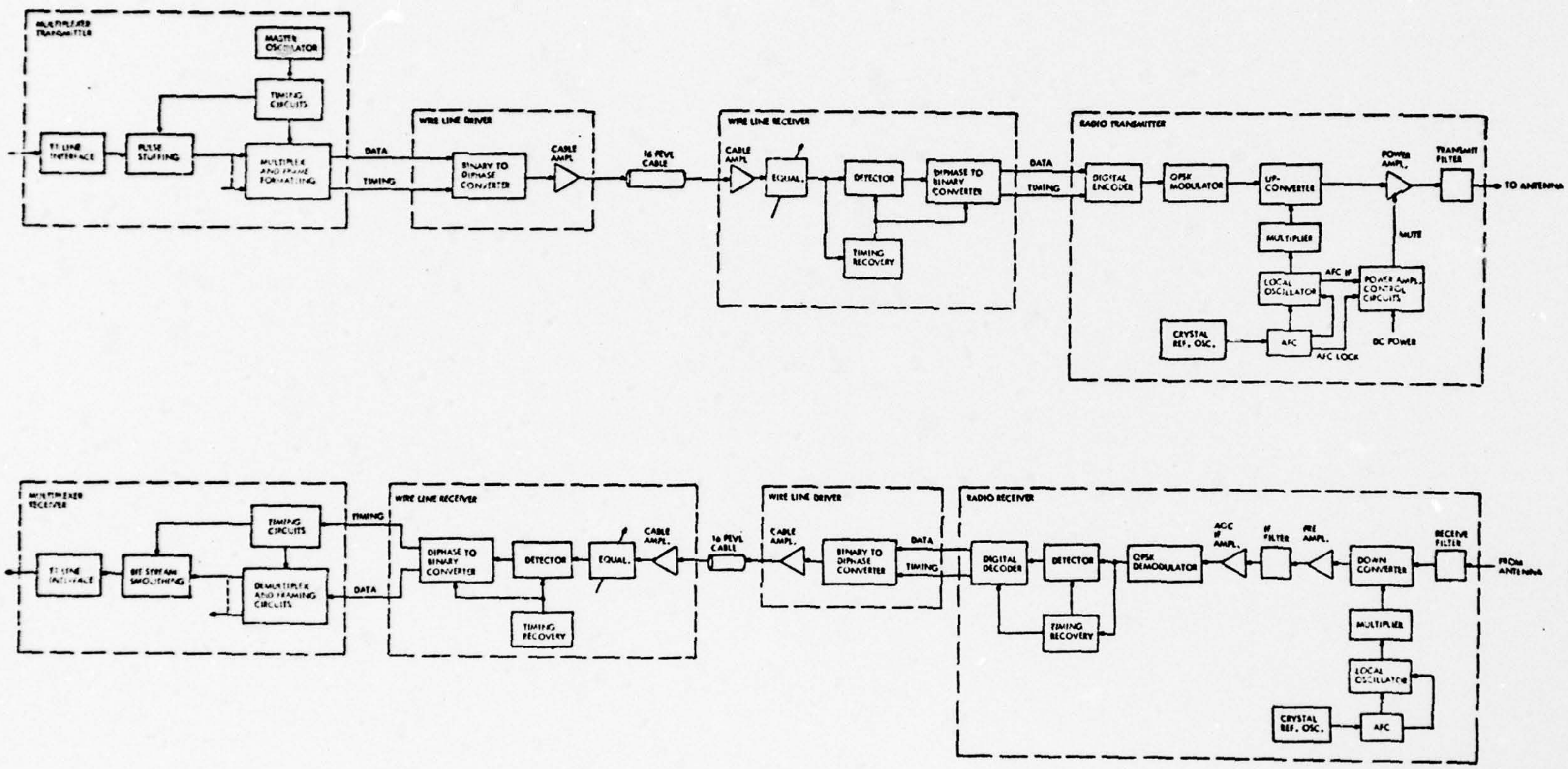


Figure A-4. RDS-80 System, Signal
Flow Diagram

The signal is next downconverted from the 10.7 to 11.7 GHz band to 70 MHz by mixing it with a reference signal derived from an AFC circuit exactly like the transmitter AFC. The 70 MHz signal is amplified and passed through an IF filter, which provides the receiver bandwidth shaping.

The 70 MHz signal is again amplified in an AGC amplifier with 55 db AGC range. The IF amplifier output goes to the demodulator, which performs two functions. It recovers a phase coherent carrier from the modulated signal and uses this signal to remove the carrier from the received signal, leaving an unreconstructed baseband digital signal (sometimes referred to as video because of its appearance on an oscilloscope).

Bit timing is recovered from the received signal in a phase locked loop and is used to sample the received data stream at the appropriate point to make the 1-0 detection decision and reconstruct the received data into a clean bit stream. After this detection process, the digital data is passed through the decoder, which performs the inverse operation of the encoder at the transmitter. The resulting output is 40 Mb/s binary NRZ data and timing on separate lines.

Between the radio receiver and multiplexer receiver the signal is transmitted through the wire line entrance link, which performs the functions described above. The resulting input to the multiplexer receiver is 40 Mb/s binary NRZ and timing on separate lines.

Common circuits of the multiplexer receiver acquire frame, demultiplex the 25 individual groups, and demultiplex the pulse destuffing information of the control channel. The timing line is processed through circuits that develop all the timing signals for the common and group circuits.

Group circuits associated with each T1 line perform bit stream smoothing, that is, smoothing out the data stream to eliminate gaps caused by the deletion of stuff pulses at the receiver. The end result of this operation is a data stream at 1.544 Mb/s that tracks exactly the bit rate of the T1 line inserted at the transmit end.

After smoothing, the 1.544 Mb/s stream passes through interface circuits that convert the binary NRZ signals to bipolar and provide the appropriate signal level and line impedance match required to interface with T1 system terminal equipment.

APPENDIX B

AN EVALUATION OF THE BASEBAND DIVERSITY
SWITCH APPLIED TO DIGITAL-FM OPERATION

R.E. Skerjanec
U.S. Department of Commerce
Office of Telecommunications
Institute for Telecommunication Sciences
Boulder, Colorado

INTRODUCTION

In planning the use of time-division multiplexed (TDM) voice and data transmission using 3-level partial response techniques and frequency modulated microwave transmission, system availability requirements dictate the need for some form of diversity techniques. The use of any of several diversity techniques raises the problem of the combining method to be used. In frequency-division multiplexed (FDM) systems, the commonly used combiner is analog (used here to mean continuous voltage addition of two or more inputs), using pre-detection or post-detection linear adders or maximal ratio combining. In these cases an improvement in signal-to-noise ratio over a single receiver is realized. An alternate method, principally used by some common carriers, is no more than a switch. The switch operates by simply selecting the better of two signals in the case of dual diversity. Considerable system improvement can be realized using this technique albeit not to the extent realized with the analog techniques.

In considering the application of these techniques to digital transmission such as that being implemented in the Frankfurt-Koenigstuhl-Vaihingen (FKV) Upgrade Project, new system parameters must be considered. Digital systems are much more sensitive to phase and time perturbations, for example, than analog systems. Equipment to be used on the FKV Upgrade Project include the DCS Microwave Radio manufactured by Collins Radio and time division multiplex units operating at 12.6 Mb/s manufactured by Vicom.

Questions were raised about what combining technique would provide the lowest risk approach for the FKV Upgrade Project within reasonable time and cost constraints. Equipment availability reduced this selection to either a maximal-ratio analog baseband combiner normally supplied with the standard

DCS Microwave Radio or a baseband switch which is a shelf item of the same manufacturer. Other manufacturers of combining equipment were not considered at this time because of the high probability of interface problems.

PROPAGATION CHARACTERISTICS AND SYSTEM PARAMETERS

Before considering the equipment in some detail, a short discussion of propagation characteristics is necessary. Line-of-sight microwave links are known to exhibit fading characteristics due to earth bulge, ground reflections and atmospheric multipath. Fading due to earth bulge and, to some degree, ground reflections can be reduced by adequate ground clearance and care in antenna height selection. Atmospheric multipath effects, on the other hand, can be most effectively reduced by the use of vertical space diversity or frequency diversity.

Multipath fading characteristics generally exhibit an amplitude distribution that is quite similar to a Rayleigh probability distribution. The Rayleigh distribution is often taken as the limiting value for multipath fading on well-designed line-of-sight microwave paths. Several prediction techniques are in existance, none of which are entirely acceptable or reliable for all locations and conditions. However, reasonably good estimates may be made by using an empirical formula based on work by Barnett (1972) of Bell Labs. This formula estimates the probability (P_{mf}) of fades exceeding a specified depth below free space for a given path and frequency. The equation is as follows:

$$P_{mf} = 6 \times 10^{-7} abf\, d^3 (10^{-M_f/10})$$

where:

$$a \begin{cases} 4: & \text{for very smooth terrain, including overwater} \\ 1: & \text{for average terrain, with some roughness} \\ \tfrac{1}{4}: & \text{for mountainous, very rough or very dry terrain} \end{cases}$$

$$b = \begin{cases} 1/2: & \text{gulf coast or similar hot, humid areas} \\ 1/4: & \text{normal interior temperate or northern} \\ 1/8: & \text{mountainous or very dry climates} \end{cases}$$

f = frequency in GHz

d = path length in kilometers

M_f = fading depth below free-space level in dB

It should be noted that this formula is good for fading depths, M_f, in excess of 10 dB and should not be used for shallower fading.

Consider two examples; worst case with $a=4$ and $b=\frac{1}{2}$ which will be identified as an overwater path located on the gulf coast and an "average" path with $a=1$ and $b=\frac{1}{4}$, corresponding to a path over average terrain with some roughness located in a normal interior temperate climate. This example is for a frequency of 8 GHz and a path length of 50 km. Using these constants in the above equation, the probability distributions shown in figure 1 are generated. Examination of these curves indicate that, even in the worst case, the probability is quite small that appreciable fade depths will be reached. To put this in different terms, if the probability of fade is considered over a reasonably long period of time, say one year, then the probability of fading may be loosely interpreted as the fraction of the year that a particular fade depth is exceeded. In these terms, a fade depth of 30 dB is exceeded for about a cumulative 9 hours in a year for the wrost case and 1 hour in the average case. If the fade depth of 40 dB is considered, the worst case reduces to one hour in a year and the average case becomes approximately 6 minutes. This analysis indicates that serious fade depths occur infrequently during the year.

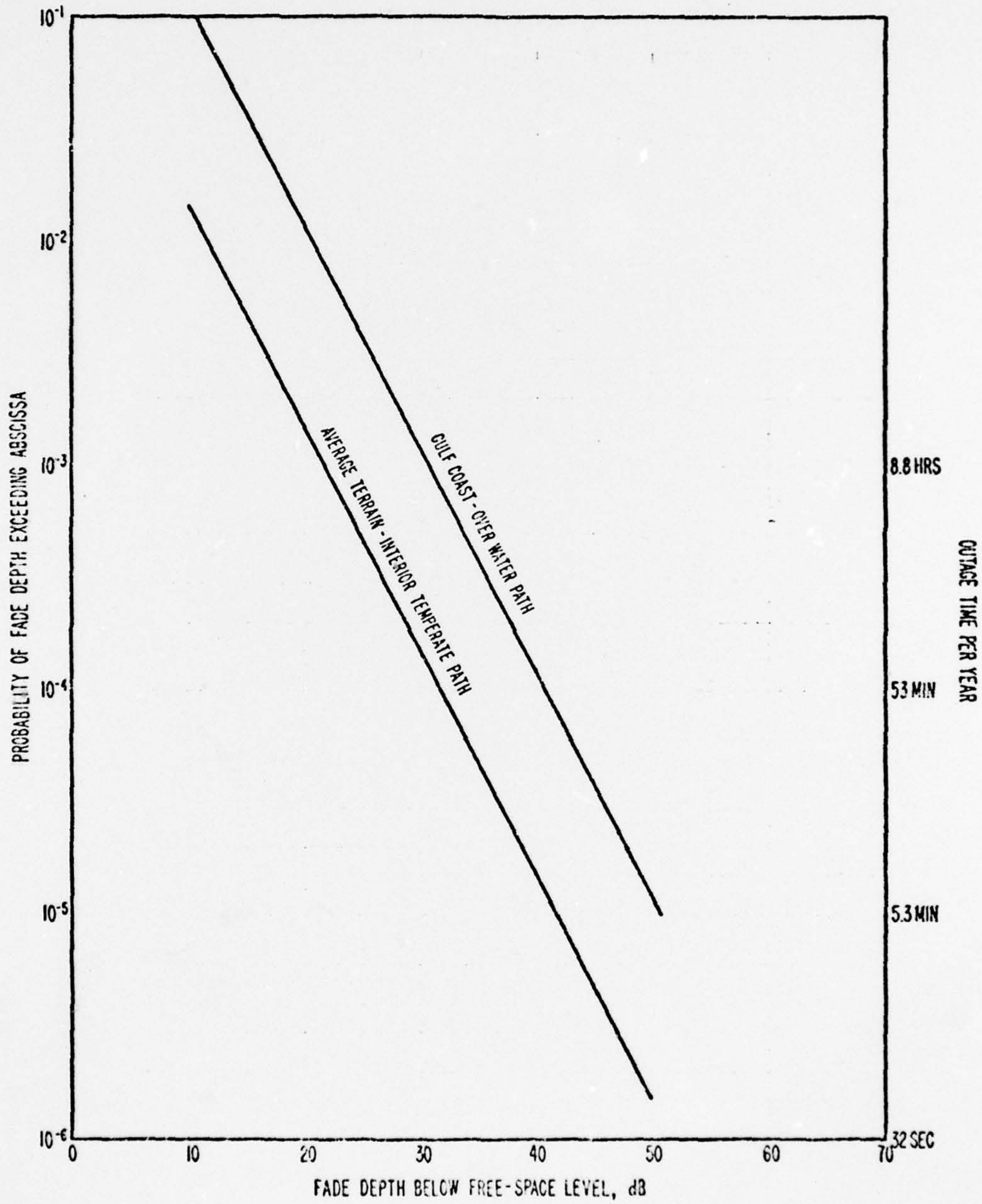

PROBABILITY OF FADE DEPTH EXCEEDING ABSCISSA
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
GULF COAST - OVER WATER PATH
AVERAGE TERRAIN - INTERIOR TEMPERATE PATH
8.8 HRS
53 MIN
5.3 MIN
32 SEC
OUTAGE TIME PER YEAR
0
10
20
30
40
50
60
70
FADE DEPTH BELOW FREE-SPACE LEVEL, dB

Figure 1.

At this point, consideration must be given to some general system design parameters that become important to this analysis. The system transfer function for digital-FM that is used in system performance specification is bit-error rate as a function of received signal level. The salient feature of this transfer function is its essentially constant bit error rate, typically in the range of 10^{-8} to 10^{-9}, for a large range of received signal levels. However, as the received level approaches a low value, the bit-error rate becomes excessive with a slope of approximately one decade increase in bit-error rate for a 1 dB reduction in received signal level; nearly a step function from acceptable performance to system failure. The point where bit-error rate begins to increase rapidly is defined here as PCM threhsold and is taken to be that received signal level for which the bit-error rate is 10^{-7}. For the equipment being considered here, this threshold is specified at a -71 dBm received signal level.

Systems design normally dictates that each link should have sufficient gain to provide a nominal median received signal level of about -25 dBm. Considering this in conjunction with the above described transfer characteristics, we see that bit-error rate perofrmance and, indirectly voice channel performance, will remain essentially constant for received signal levels between -25 dBm and -71 dBm. This corresponds to a fade depth of approximately 45 dB. Using this fade depth and the distribution in figure 1, the probability of exceeding a 45 dB fade depth, in the worst case, is $3.75\text{x}10^{-5}$, or, in terms of time, a cumulative 20 minutes per year. Put in different terms, a well designed system will perform satisfactorily (i.e., above threshold) for all but a cumulative 20 minutes in a year. Therefore, the system designer needs

to be concerned about improving system performance for a small fraction of the year, assuming a well designed system to this point.

The above discussion evolved around the amplitude statistics of the propagation path and the static transfer characteristics of the equipment. Other parameters are of concern in this analysis. In terms of digital combining, adequate information is needed on the dynamic phase variation during anomalous propagation conditions. Of particular interest to the problems of diversity operation, the relative time differential between two received signals must be known or assumed. This type of information to date is meager, to say the least. Consider a 12.6 Mb/s data rage, corresponding to a bit interval of 80 nsec. Further, assume that a differential time of arrival greater than ¼ of a bit interval or 20 nsec will be detrimental. Intuition, which may be to a degree all that we have to go on, says that the probability of delays in excess of 20 nsec would be extremely small, probabily less than that expected for exceeding fade depths of, say 40 to 50 dB. However, this analysis is offered with reservation, since definitive data are almost non-existent.

The foregoing discussion is an attempt to put the likelihood of occurrence of the anamolous conditions in perspective where consideration must be given to providing protection against such anamolies. This protection takes the form of diversity, specifically vertical space diversity for the FKV project.

Since proper system design will provide a large tolerance to signal fading, the transmission channel will have negligible influence on satisfactory voice or low-speed data communication service except for a very small fraction of the year. Only during this small fraction of the year when depressed signal

levels are expected is the necessity for diversity reception apparent and then only over a relatively narrow range of received signal levels near PCM threshold. Recalling that a maximal-ratio baseband combiner continuously utilizes both diversity signals over the full range of received signal level variation and the uncertainty of definitive phase information, the more technically conservative choice must be the baseband switch provided that its range of operation can be adequately controlled.

DESCRIPTION OF SWITCH CHARACTERISTICS AND MODIFICATION

The baseband switch under consideration is the 23P2-4MW, manufactured by Collins Radio. Briefly, this switch is designed to select one of two input basebands for use as the operating signal. As this in-service half degrades with respect to the other available input, the switch transfers to the better input. The sensing and comparator circuits contain a dead-zone, in this case 5 dB, where the in-service half must degrade 5 dB below the other available input (out-of-service half) before the switch transfer takes place. Initial verbal information from Collins Radio indicated an increased dead-zone at high signal levels.

Sensing for switch operation includes detection of radio pilot presence which is an on-off control. Provisions are also made for other on-off inputs, but are not used in this particular configuration. The most important elements sensed are the AGC voltages of the two receivers. Switch operation is primarily determined by the dynamic differential between the two AGC voltages.

Switching time is specified by Collins Radio as that "which occurs from the 3 dB point of a signal being switched off to the 3 dB point of one being switched on" and shall

not be more than 1 microsecond. Tests conducted at Collins Radio in July, 1973, oriented towards optimization indicated an occasional error burst of 4 to 12 errors. Based on these measurements, and with allowance for measurement and production tolerances, specifications were prepared including limiting the error burst during switch-over to less than 100 errors. Discussions were held with the designer of the switch on reduction of switching time on this unit. Indications are that switching time could be reduced some, but only at the expense of greatly increased insertion loss.

As a result of this specification, concern was raised about the average error-rate exceeding requirements at high signal levels. The cause of these excessive errors would be two received signal inputs fluctuating over a sufficient amplitude range and rapidly enough to cause frequent switch over. During normal propagation conditions, such as that experienced during daylight hours through a well-mixed atmosphere, the received signal levels will fluctuate slowly and in most cases over an amplitude range sufficiently small to be of no concern. However, during anomalous conditions, such as those sometimes experienced during night-time hours exhibiting something close to a Rayleigh characteristic with relatively frequent, wide dynamic range fluctuations, concern over error bursts due to frequent switch-over may be well founded.

The most direct solution to this problem appeared to be the deactivation of the switching function above some level sufficiently close to the PCM threshold. This is based, in part, on the bit-error-rate-received signal level characteristic of the equipment. If the switch did, in fact, have a 5 dB dead-zone, a good choice of the switch activation-deactivation threshold would be 5 to 6 dB above PCM threshold. In this case, the switch would be fully active and performing normally

as received signal level approached PCM threshold. At higher levels, the switch would remain on one input without switch-over, maintaining satisfactory bit-error rate performance criteria.

An examination of the circuit diagram along with discussions with Collins personnel revealed that there was a clamping element in the sensing-comparator circuit that did, in fact, perform the desired deactivating function, although not at the desired received signal level. This clamping element was a zener diode with a nominal value of 5.6 volts in the standard unit.

TEST RESULTS

It was decided at this point to visit the Collins Radio plant to attempt the desired modification, perform measurements and better understand the switch function.

All measurements and specifications on the switch are in terms of AGC voltage. Normal AGC voltage range on the DCS Microwave Radio is from -8 volts to -2 volts, corresponding to RF input levels of -22 dBm to -82 dBm. The following discussion will be primarily in terms of AGC voltages for convenience. However, conversion to received signal levels may be made using the above relationship which is approximately linear.

A standard switch unit was modified by replacing the 5.6 V zener diode clamp with a 3.6 V zener diode clamp. This change was made in an effort to move the deactivation threshold from an AGC voltage of -5.6 V to -3.6 V, corresponding to a received signal level of -66 dBm.

Bench tests were performed at the Collins Radio plant. Two modified units were installed in a test jig that simulated normal receiver cross-connect functions. The switches were controlled with two variable power supplies to simulate the

two receiver AGC voltages. Additionally, an 8.5 MHz pilot was provided by a signal generator to prevent "loss of pilot" over-ride. The tests were conducted to determine the differential requirements for switch-over. These tests were generally performed by fixing one AGC voltage and slowly changing the other to a point of switch-over. This process was repeated for various fixed voltages.

The results are shown in figure 2 in terms of differential voltage required for switch-over as a function of AGC voltage just prior to the fade. A clearer presentation of these data is shown in figure 3 where the in-service AGC voltage at switch-over is plotted as a function of AGC voltage just prior to the fade. An important point to note in both of these figures is that the out-of-service AGC voltage is maintained constant at the value just prior to the fade.

These characteristics, while taken under static conditions, do give an indcation of what the dynamic characteristics might be like. Figure 3 in particular shows that there will not be switch-over until the in-service AGC voltage drops to -3.2 to -3.6 V, provided the out-of-service AGC voltage lies within the range of -4 to -8 volts. This is the realization of the characteristic hypothesized earlier where the switch is essentially deactivated above some threshold, in this case a nominal 3.6 V AGC, and operates normally for AGC voltages between -2 and -3.2 V.

CONSIDERATION OF TOLERANCES

Up to this point, it was assumed that the two AGC characteristics were matched and linear and the clamping diode voltage has zero tolerance. Attention must be given now to what effects tolerances have on the performance of the switch.

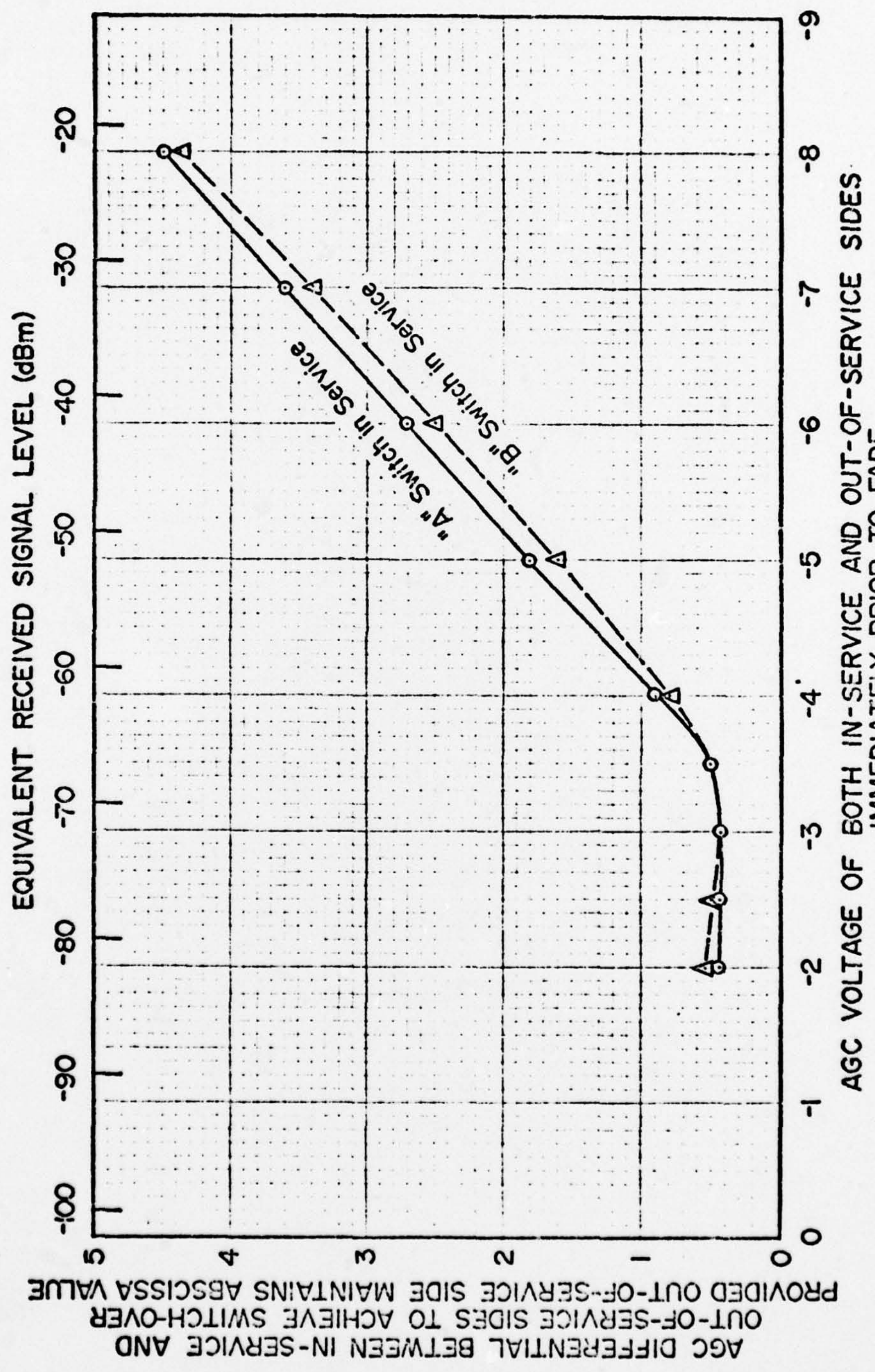
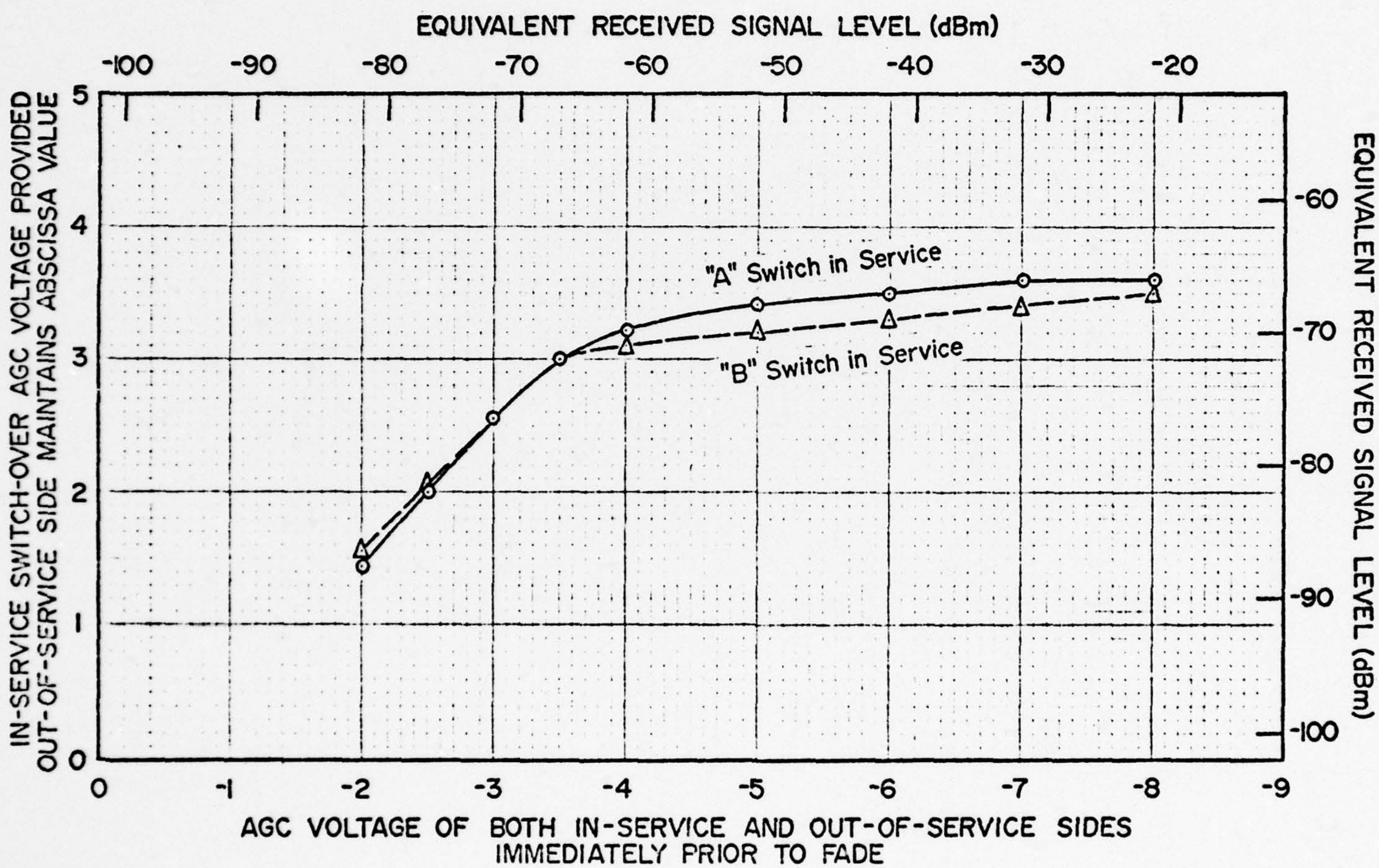

EQUIVALENT RECEIVED SIGNAL LEVEL (dBm)
-100
-90
-80
-70
-60
-50
-40
-30
-20
AGC DIFFERENTIAL BETWEEN IN-SERVICE AND
OUT-OF-SERVICE SIDES TO ACHIEVE SWITCH-OVER
PROVIDED OUT-OF-SERVICE SIDE MAINTAINS ABSCISSA VALUE
0
1
2
3
4
5
"A" Switch in Service
"B" Switch in Service
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
AGC VOLTAGE OF BOTH IN-SERVICE AND OUT-OF-SERVICE SIDES
IMMEDIATELY PRIOR TO FADE

Figure 2.



EQUIVALENT RECEIVED SIGNAL LEVEL (dBm)
-100 -90 -80 -70 -60 -50 -40 -30 -20
IN-SERVICE SWITCH-OVER AGC VOLTAGE PROVIDED OUT-OF-SERVICE SIDE MAINTAINS ABSCISSA VALUE
0 1 2 3 4 5
"A" Switch in Service
"B" Switch in Service
EQUIVALENT RECEIVED SIGNAL LEVEL (dBm)
-60 -70 -80 -90 -100
0 -1 -2 -3 -4 -5 -6 -7 -8 -9
AGC VOLTAGE OF BOTH IN-SERVICE AND OUT-OF-SERVICE SIDES IMMEDIATELY PRIOR TO FADE

Figure 3.

First consideration is the deactivate threshold. This threshold is determined by the zener diode clamp and the diode is specified with a ±5% tolerance. For the 3.6 V zener, the tolerance is ±0.18V, or in terms of received signal level, the variation will be approximately ±1.8 dB. The other area of major concern is the degree of linearity of the AGC received signal level characteristics and the DC offset between the AGC characteristics within the same diversity set. Information obtained from Collins Radio indicates that the AGC linearity as specified must be within ±200 mV from -2 to -8 V. Further, the AGC alignment procedure includes the adjustment of two point on the AGC curve to absolute levels, i.e., -7.2 V ± 30 mV for an RF input of -30 dBm and -5.2 V ± 30 mV for an RF input of -50 dBm. Taking the worst case where all the tolerances add, the deactivate threshold will fall ±410 mV away from the expected value. In terms of received signal level, this would be ±4 dB and in the worst case, the switch would become normally active at -70 dBm, 1 dB above specified PCM threshold. At this point, this tolerance may not be too serious.

On the brighter side, there appears to be sufficient adjustment within the AGC circuitry to match the two receiver AGC curves much closer than production alignment now allows. Further, there is some adjustment within the switch comparator circuit to compensate for gain differences between the two AGC input voltages.

CONCLUSIONS AND RECOMMENDATIONS

In summary, for the FKV project, the most cost-effective, minimum technical risk approach to combining baseband digital data would be to use a modified baseband switch. The modification would include replacing the 5.6 V limiting zener diode with a 3.6 V diode. Existing tolerances appear to be acceptable

at this time. However, if the production tolerance spread becomes too large, premium tuning may be necessary and may best be done by USACC or the EF&I contractor.

Throughout this discussion, questionable areas have surfaced. It is highly recommended that some of these areas be investigated further, particularly by measurement on the FKV system during normal operation. These include frequency of operation of the modified switches, particualarly during anomalous propagation conditions, and differential time of arrival of the baseband signals from the two diversity paths on selected links. This information, along with more detailed measurements of the operation of a baseband analog combiner and its effects on bit-error rate may provide better design techniques for installations subsequent to the FKV project.

REFERENCES

Barnett, W.T. (1972), Multipath Propagation of 4, 6 and 11 GHz, Bell System Tech. J., 51, No. 2.

APPENDIX C

FKV Suggested Operational Practices[1]

1. Methodology to determine the level of system performance through the continued analysis of alarms and other built-in indicators.
2. Alternate routing, particularly, of high priority circuits.
3. Prompt, effective fault isolation and repair using either on-site or mobile maintenance concepts.
4. A measurable indication of time availability, such as, an accumulation of digroup alarm durations.
5. The elimination of periodic or routine inspections or tests unless it can be demonstrated from experience on the newer systems that any particular parameter is inordinately unstable.
6. The activities of site personnel should be combined so that there would be system operators rather than separate technical control and microwave maintenance personnel.
7. Station logs and records are intended to be a concise history of system operation and the primary source of information about the system. As such, they must contain clear detailed technical information on any perturbation within the system and should not be degraded to a mere visitor

1. R.E. Skerjanec, J.E. Farrow, FKV Pilot Digital System Evaluation, Institute of Telecommunications Sciences, July 1977, Vol. I, pp. 6-7.

register and sign-in form for personnel.

8. The final use of station logs should be clearly stated so that these uses will be known to those creating the logs and will have some influence on their contents.

9. Reporting criteria must be carefully reviewed and corrected so that short, recurrent interruptions of traffic are reported as well as those that exceed 10 minutes in duration.

10. The isolation and correction of circuit problems should be emphasized as opposed to the human aspect of blame for errors.

11. A competent, dedicated engineer should be placed within a system or segment of the system for the express purpose of being continually aware of the general status of the system. This would be accomplished by frequent visits to the sites, reading of station logs, conversing with station personnel and observing system operation for himself. In addition, he should report directly to the staff operating command, and should be expected to expedite the repair or restoral of the system as required.

12. An order of priorities for both operations and maintenance should be developed so that urgent attention is given in the areas of greatest need.